

See discussions, stats, and author profiles for this publication at: <https://www.researchgate.net/publication/291425187>

# How the unique properties of soil kaolin affect the fertility of tropical soils

Article in *Applied Clay Science* · January 2016

DOI: 10.1016/j.clay.2016.01.007

CITATIONS

13

READS

632

2 authors:



R. J. Gilkes

University of Western Australia

388 PUBLICATIONS 9,207 CITATIONS

[SEE PROFILE](#)



Nattaporn Prakongkep

Land Development Department

22 PUBLICATIONS 213 CITATIONS

[SEE PROFILE](#)

Some of the authors of this publication are also working on these related projects:



Research on Phosphorus Soil Tests, Rockphosphate and superphosphate application in soil and Phosphorus Soil Chemistry [View project](#)



Iron Ore Characterisation [View project](#)

Dear Author,

Please, note that changes made to the HTML content will be added to the article before publication, but are not reflected in this PDF.

Note also that this file should not be used for submitting corrections.



Contents lists available at ScienceDirect

Applied Clay Science

journal homepage: [www.elsevier.com/locate/clay](http://www.elsevier.com/locate/clay)

1 Research paper

## Q2 How the unique properties of soil kaolin affect the fertility of tropical soils

Q3 Robert J. Gilkes<sup>a,\*</sup>, Nattaporn Prakongkep<sup>b</sup><sup>a</sup> School of Earth and Environment, University of Western Australia, Crawley 6009, Australia<sup>b</sup> Soil Mineralogy and Soil Micromorphology Research Group, Office of Science for Land Development, Land Development Department, Bangkok, Thailand

## ARTICLE INFO

## Article history:

Received 22 August 2015

Received in revised form 7 January 2016

Accepted 8 January 2016

Available online xxxx

## Keywords:

Kaolin

Crystal size

Surface area

Cation and anion exchange

## ABSTRACT

The kaolin (*s.l.*) in many tropical soils is distinctly different from most specimen and industrial kaolins. Crystal structure is highly disordered and crystal sizes are much smaller than for specimen and industrial kaolins. The crystal habit of soil kaolins is diverse ranging through euhedral hexagonal and anhedral platy, spheroidal and tubular. The specific surface of soil kaolins is higher than for most industrial kaolins. Consequently, cation and anion retention capacities are higher although there is no compelling evidence that the high structural disorder of soil kaolin is associated with a greater specific reactivity of the kaolin surface. A small amount of ferric iron substitutes for octahedral Al but there is generally little or no substitution of other cations. Soil kaolin commonly contains minor amounts of potassium but this is present in mica layers within, attached or associated with kaolin crystals so that potassium is not within the kaolin structure. Due to its considerable chemical reactivity soil kaolin helps provide an effective substrate to support agriculture and other land uses in the tropics.

© 2015 Published by Elsevier B.V. 24

## 1. Introduction

Should a paper on the significance of soil kaolin (*s.l.*) be included in a publication that is mostly concerned with commercial clay minerals? Our response is simply that kaolin dominated soils are abundant in the wet tropics and as a high proportion of the world's population relies on these soils for the agriculture that produces food and fiber (Fig. 1) we should be aware of these kaolins. Kaolin enables these soils to provide clean water and buffer the environment against diverse contaminants. To the many people in this region the unique properties of soil kaolin are of critical importance so that the mineral deserves the research attention that it has received in recent decades. We have chosen to use the term kaolin rather than kaolinite as soil kaolins may include minerals that might be classified as variously ordered kaolinites, halloysite, nacrite and dickite but are not readily distinguished by routine examination. We are therefore considering the kaolin group of minerals as discussed by Guggenheim et al. (1997) but also include halloysite in its variously hydrated conditions.

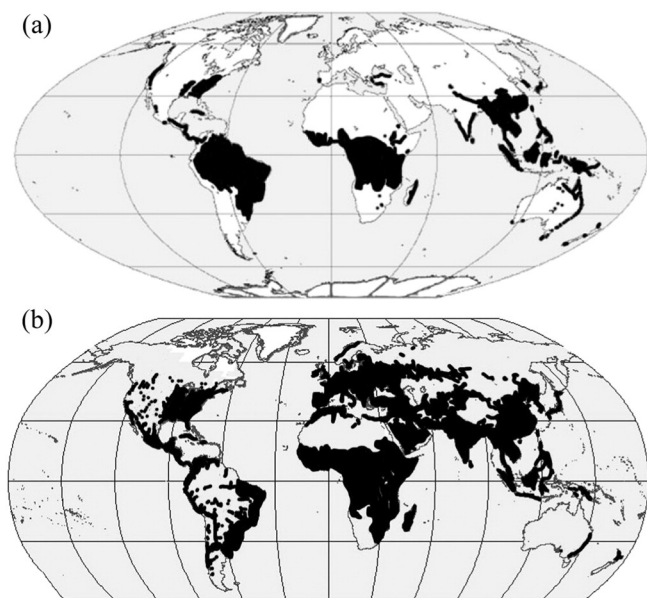
Soil kaolins are as diverse as those used in industry but they may differ from industrial kaolins in several important respects. The kaolin present in the solum (the uppermost "living" part of the soil) is commonly different from kaolin in the underlying saprolite or sediment where the kaolin may resemble many industrial kaolins; consisting of large, structurally ordered, euhedral crystals (Varajão et al., 2001; Hughes et al., 2009). The specimen kaolins described in many publications commonly consist of large, euhedral and highly ordered crystals (Hart et al., 2002; Hughes et al., 2009). Soil kaolin crystals are mostly

very small with habits ranging from euhedral hexagonal plates through anhedral plates to tubular and spherical forms. Consequently, specific surface area (SSA) is high resulting in substantial cation and anion retention capacities which are of great benefit to agriculture as cationic and anionic forms of plant nutrient elements are retained against leaching under the high rainfall condition of the wet tropics. Similarly soil kaolin can reduce the mobility of toxic ions and harmful synthetic organic molecules in soils thereby moderating contamination of food crops and water resources. An important and desirable property of soil is its capacity to retain the water received from rainfall or irrigation and then release this water to plants in response to the demands of the growing plant transmitted through the root system. What is required is a stable, porous soil structure with an abundance of connected pores in the 0.1–10 μm size range. Many tropical soils with kaolin as the dominant clay mineral have exactly this characteristic and consequently they are less sensitive to drought conditions and water is used efficiently. The low bulk density and structural stability of some kaolin-rich tropical soils, notably oxisols, are thought to be a consequence of their stable low-density, porous "card house" structure where kaolin plates are secured in place by iron oxide crystals attached to kaolin crystals through electrostatic attraction (Tawornpruek et al., 2006). Kaolin has a negative surface charge and iron oxides have a positive surface charge at the acid pH conditions prevalent in tropical soils (Khawmee et al., 2013).

A commonly held view of the mineralogical basis of chemical soil fertility is that the clay fraction contains micrometric grain of mica, vermiculite, chlorite, feldspar, pyroxene, and other primary minerals (Retallack, 1990). These minerals contain several plant nutrient elements that are released to plants by dissolution and exchange reactions in the soil. This is certainly the situation in mid-latitudes where many soils have formed on glacial residuum which includes alluvium and

\* Corresponding author.

E-mail address: [bob.gilkes@uwa.edu.au](mailto:bob.gilkes@uwa.edu.au) (R.J. Gilkes).



**Fig. 1.** (a) The global distribution of kaolinitic soils (based on ISSS, 1998) and (b) The global distribution of medium to high population density showing that the highly populated tropical region commonly has kaolin-rich soils (based on CIESIN–Columbia University, 2014).

loess transported for long distances by wind and water from regions of former glacial activity. Indeed some tropical soils have also been derived from rock debris resulting from tectonic activity and vulcanicity and these soils are consequently fertile. Large active river systems in the tropics deposit mineral rich alluvium in flood plains and deltas which support fertile productive soils (Young, 1976). However, much of the tropical and subtropical zone is occupied by ancient upland landscapes mantled by deep, highly weathered regolith with kaolin and iron oxides dominating the clay fraction of the solum. Quartz and a few resistant primary minerals comprise the silt and sand fractions which do not contribute significant amounts of nutrients to plants (Darunsontaya et al., 2012). Under these circumstances, it might be anticipated that the chemical fertility of the prevalent kaolinitic soils will be poor and this is usually the case. Soil organic matter may provide a reserve of some plant nutrients and is of particular value in highly weathered kaolinitic soils but the soils generally remain infertile. There is evidence for potassium and other plant nutrient elements being present in minor concentrations in soil kaolin and these elements may be at least partly available to plants (Singh, 1991).

It is evident from this overview that the properties of soil kaolins are rather different from specimen kaolinite and those kaolins utilized by industry and also that the properties of kaolin that are of particular interest to soil scientists may not coincide with those of researchers into the properties and performance of industrial and specimen clays. In this paper, we review the present state of knowledge of soil kaolin and attempt to identify relationships between chemical, morphological and structural properties of soil kaolins. We restrict our review to those papers that have used the same analytical procedures and we have been alert to data having been reproduced in several papers thus avoiding duplication of data in our summaries of experimental results.

## 2. Preparing soil kaolin for analysis

It is impossible to separate pure kaolin samples from soils as the clay fraction of all soils contains micrometric crystals of diverse accessory minerals. Consequently, measurements are made on clay separates including clays that have been chemically treated to remove Fe/Mn oxides, carbonate minerals and organic matter, but these separates are

still not pure kaolin. This is a particular problem for measurements of surface properties of soil kaolin (SSA—specific surface area, ion exchange and retention, surface charge density) and bulk chemical composition where results are invariably confounded to some extent by the presence and properties of impurities. Crystallographic properties of kaolin such as basal spacing, peak shape and crystallinity indices are not very sensitive to the presence of small amounts of impurities. Transmission electron micrographs need to be interpreted with caution as micrometric particles may be impurities rather than being kaolin crystals. This problem can be avoided if individual particles are analyzed by X-ray spectrometry in the TEM (EDS) to confirm that they are kaolin although this is a time consuming process (Singh and Gilkes, 1995).

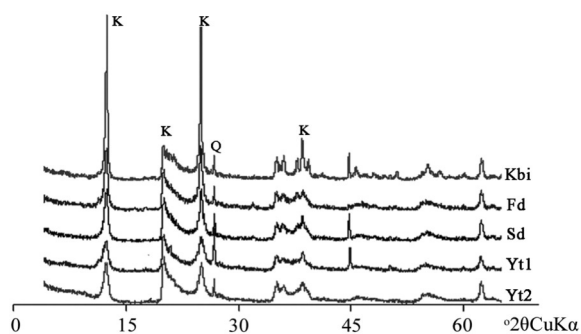
The common pretreatments of soil clay samples consist of (i) digestion in hydrogen peroxide solution at near neutral pH to remove organic matter although this treatment might oxidize structural ferrous ion in clay minerals (ii) removal of free Fe/Mn oxides by repeated digestion in DCB (dithionite–citrate–bicarbonate) solution which reduces and dissolves these oxides. The structural Fe in clay minerals can be reduced by this treatment which will then affect the layer charge of the minerals (Stucki, 2006). It is usual to check the purity of separated soil kaolins using XRD but this technique has limited sensitivity especially for highly disordered layer silicates and amorphous aluminosilicates such as allophane. The use of synchrotron XRD can provide greater sensitivity for the recognition of quartz, anatase, rutile, crandallite and other common crystalline impurities in kaolin samples but is not equally effective for determining poorly ordered silicate minerals. Other analytical techniques such as IR spectrometry and thermal analysis may be used to detect impurities in kaolin concentrates but these techniques are too insensitive to distinguish minor amounts of most mineral species.

Thus, it may not be possible to quantitatively determine the amounts of impurity minerals in kaolin concentrates consequently accurate corrections of chemical analyses can not be made. The use of Rietveld XRD analysis (Hillier, 2000) in recent years has greatly improved the quantification of minerals in clay concentrates so that reliable correction for some crystalline impurity minerals is now possible; however the sensitivity of XRD techniques for minor and disordered constituents remains poor. This is a particular limitation when attempts are made to allocate minor elements (e.g. Cr, Zn, Pb) in kaolin concentrates to mineral species. Thus, for example it may not be possible to conclude whether  $\mu\text{g g}^{-1}$  amounts of Cr are in the structure of kaolin (Singh and Gilkes, 1991) or are in minor amounts of associated chromite. Unfortunately, EDS combined with TEM lacks sufficient sensitivity to determine trace levels of metals in single crystals of kaolin. With these reservations in mind, we will now turn our attention to what is known of the properties of soil kaolin.

## 3. Properties of soil kaolin

As mentioned in the introduction some mature leached tropical soils may contain large, euhedral kaolin crystals with a high degree of structural order. This kaolin has generally been inherited from deep regolith or sedimentary rocks and does not have a pedogenic origin (Varajão et al., 2001). More commonly kaolin in the solum consists of small crystals with a low degree of structural order (Brindley and Brown, 1980). Typical random powder XRD patterns of deferrated kaolin clay from tropical soils are shown in Fig. 2 where only basal (001) and two dimensional order (hk) diffraction peaks of kaolin are present. The prism (hkl) reflections that are characteristic of well ordered kaolin are absent due to the high extent of b-axis disorder in soil kaolins. The great width of the basal (001, 002) reflections is predominantly due to the small crystal size in the c-axis direction which can be estimated from diffraction line broadening using the Scherrer equation (coherently diffracting domain size CSD) (Brindley and Brown, 1980).

The basal spacing ( $d(001)$ ) of kaolin appears to increase from 0.715 nm to about 0.730 nm as CSD decreases from 40 to 6 nm



**Fig. 2.** X-ray diffraction patterns of the randomly oriented deferrated clay fraction of red Ultisols, showing the weak broad reflections typical of microcrystalline, b-axis disordered kaolinite with no other clay minerals (K = kaolinite, Q = quartz) (Trakoonyingcharoen et al., 2006).

(Fig. 3). This is an artifact due to displacement of the maximum of the broad 001 reflection that is associated with the steep rise in structure and angular factors with decreasing  $2\theta$ . The data shown in Fig. 3 come from publications on soil kaolin from Indonesia, Thailand, Brazil and Australia together with data for specimen kaolins. Some of the deviation of data from the fitted curve is probably due to differences in the analytical methods used by the different authors.

The chemical composition of soil kaolin is quite variable and commonly does not conform to the ideal composition (39.5%  $\text{Al}_2\text{O}_3$ , 46.6%  $\text{SiO}_2$ ). This diversity is illustrated in Fig. 4 for data for soil kaolin from diverse localities. The median value for  $\text{SiO}_2$  (46.33%) approximately coincides with the ideal composition but the median  $\text{Al}_2\text{O}_3$  concentration is significantly smaller. There is considerable variation about these values which can be ascribed to the presence of impurity minerals and to experimental error but it seems probable that soil kaolin commonly differs in composition from the ideal formula. It has been reported that many soil kaolins contain structural Fe with levels of 1–4%  $\text{Fe}_2\text{O}_3$  being commonly observed (Hart et al., 2002). Higher values of the iron concentration in soil kaolin reported in the literature (up to 11%  $\text{Fe}_2\text{O}_3$ ) are probably mostly associated with the presence of iron oxides and other impurities. The iron in kaolin crystals is in octahedral coordination as ferric ions replacing aluminum ions (St. Pierre et al., 1992) a substitution which has no impact on the layer charge but may affect other crystal properties as will be discussed later.

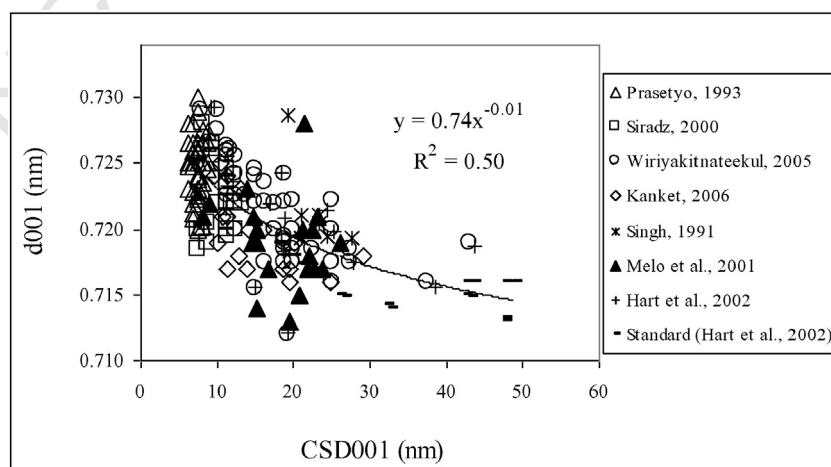
Soil kaolin commonly appears to contain potassium at concentrations less than 1%  $\text{K}_2\text{O}$ . It is difficult to determine the location of this

potassium but studies by Chi and Eggleton (1999) and Darunsontaya et al. (2012) indicate that minor amounts of muscovite-like mica can occur as interlayers and surface layers on kaolin crystals or as minor amounts of coexisting muscovite that cannot be detected by conventional or synchrotron XRD techniques. Very detailed studies of soil kaolin using TEM/EDS on ultramicrotomed sections of kaolin crystals have revealed various configurations of muscovite with kaolin. In Fig. 5a–b, the presence of a nanometric crystal of mica (1.0 nm spacing) on the surface of a complex crystal(s) of kaolin (0.7 nm) is revealed.

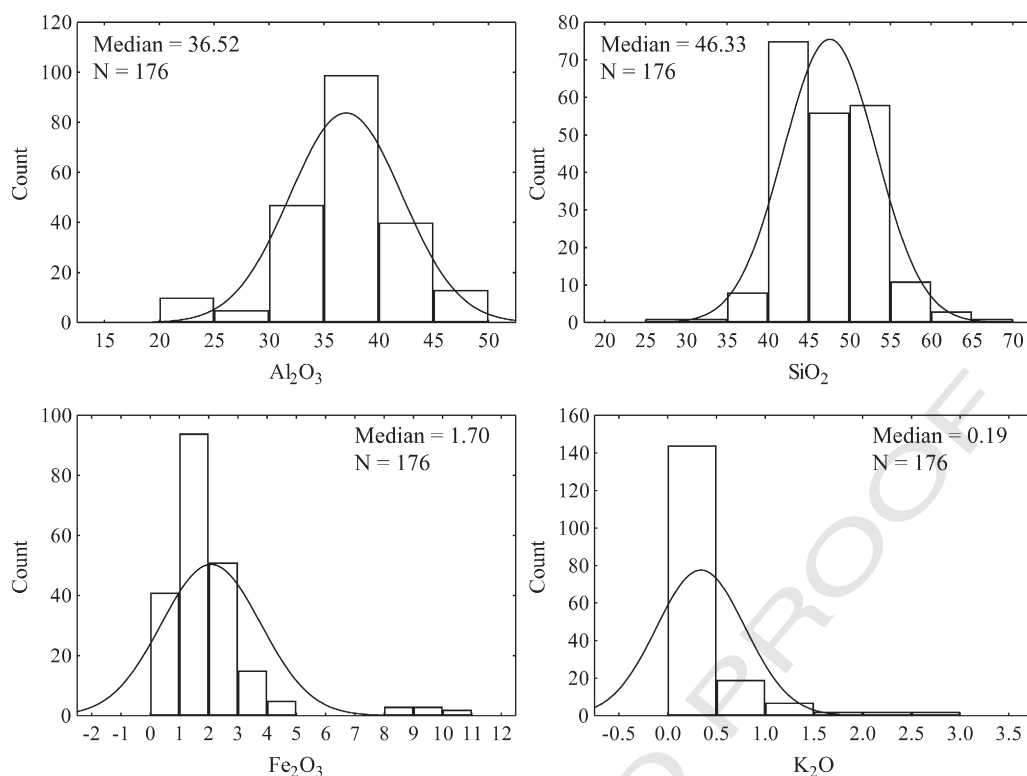
The size and shape of kaolin crystals in tropical soils is highly diverse (Fig. 6a,b,c) with small anhedral platy crystals dominating and with some, tubular and spheroidal crystals. The large euhedral, hexagonal crystals (Fig. 6d) that are characteristic of many industrial and specimen kaolins are uncommon and where they occur in the solum may have been inherited from saprolite or sedimentary rocks. The majority of soil kaolins are mostly composed of small (0.1  $\mu\text{m}$ ) platy crystals and these may be anhedral to euhedral hexagonal with all morphologies giving XRD patterns characteristic of a highly b-axis disordered structure. There is no relationship between the degree of euhedral character of kaolin crystals and structural order. Some soil kaolins contain a considerable proportion of tubular (halloysite) or spheroidal crystals and these are commonly associated with soils derived from volcanic detritus or deep regolith (Siradz, 2000; Kew and Gilkes, 2007).

The specific surface area (SSA) of kaolin in tropical soils varies greatly (10–90  $\text{m}^2 \text{g}^{-1}$ ) (Fig. 7) and this nearly 10-fold range in SSA is a consequence of a similar large variation in crystal size (CSD 001) (Fig. 3). Many industrial and specimen kaolins have much smaller values of SSA. Overall there is no close consistent relationship between SSA and iron content of kaolin but there may be weak positive relationships for individual data sets. The high values of SSA approach those typical of illite (40–65  $\text{m}^2 \text{g}^{-1}$ ) (Dogan et al., 2007) which is a clay mineral that provides substantial cation exchange capacity to some soils (10–40  $\text{cmol kg}^{-1}$ ) (Borden and Giese, 2001).

There is no systematic relationship between SSA and cation exchange capacity (CEC) (Fig. 8) as is shown by data for soil kaolin derived from seven publications. These data indicate that the CEC of soil kaolin may be as high as 23  $\text{cmol kg}^{-1}$  which is much higher than values of 2–3  $\text{cmol kg}^{-1}$  for standard mineral kaolins (Van Olphen and Fripiat, 1979). It is likely that the largest values of CEC shown in Fig. 8 are due to impure samples, and use of inappropriate methodology including measurement of CEC at a high pH where the pH-dependent surface charge of kaolin has increased. The line that describes the lower limit of the data in Fig. 8 corresponds to a surface charge density of 0.1  $\text{C m}^{-2}$  which is smaller than the value of 0.18  $\text{C m}^{-2}$  determined



**Fig. 3.** Data from published studies on the relationship between the basal spacing ( $d_{001}$ ) of soil kaolin from tropical soils and crystal size (coherently scattering dimension (CSD 001)). Data for standard mineral kaolins are included.

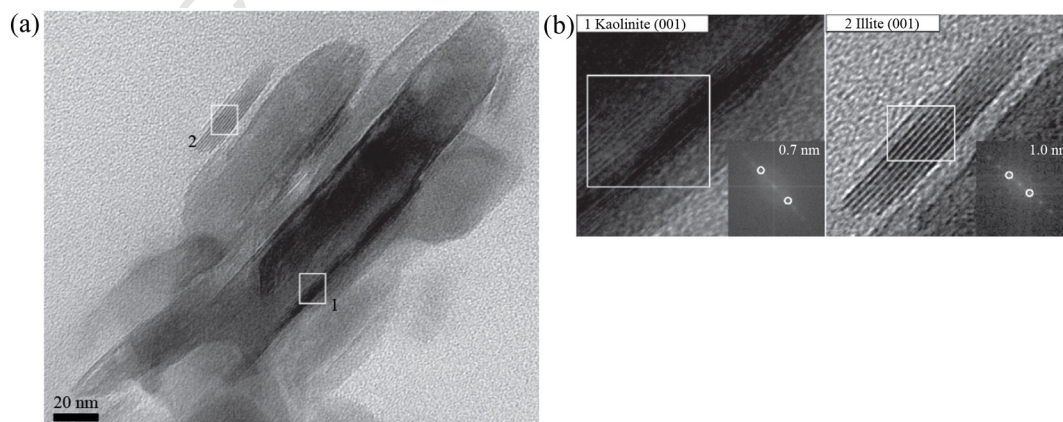


**Fig. 4.** The chemical composition of purified soil kaolin. These 176 kaolins were extracted from tropical soils, data from 8 publications and all samples contain minor amounts of impurities (St. Pierre et al., 1992; Melo et al., 2001; Hart et al., 2003; Wiriyakitnateekul, 2005; Kanket, 2006; Trakoonyingcharoen, 2005; Hu and Yang, 2013; Qiu et al., 2014).

260 by Kanket et al. (2005) for Georgia reference kaolinite although the average value for these data of about  $0.2 \text{ C m}^{-2}$  is similar. It seems that the CEC of soil kaolin may mostly reflect the size of crystals rather than the different natures of the kaolin crystal surfaces contributing to cation exchange, but this interpretation remains speculative. The highly disordered internal structure does not appear to be reflected in different surface characteristics, possibly because b-axis disorder simply translates kaolin layers without modifying them (Brindley and Brown, 1980).

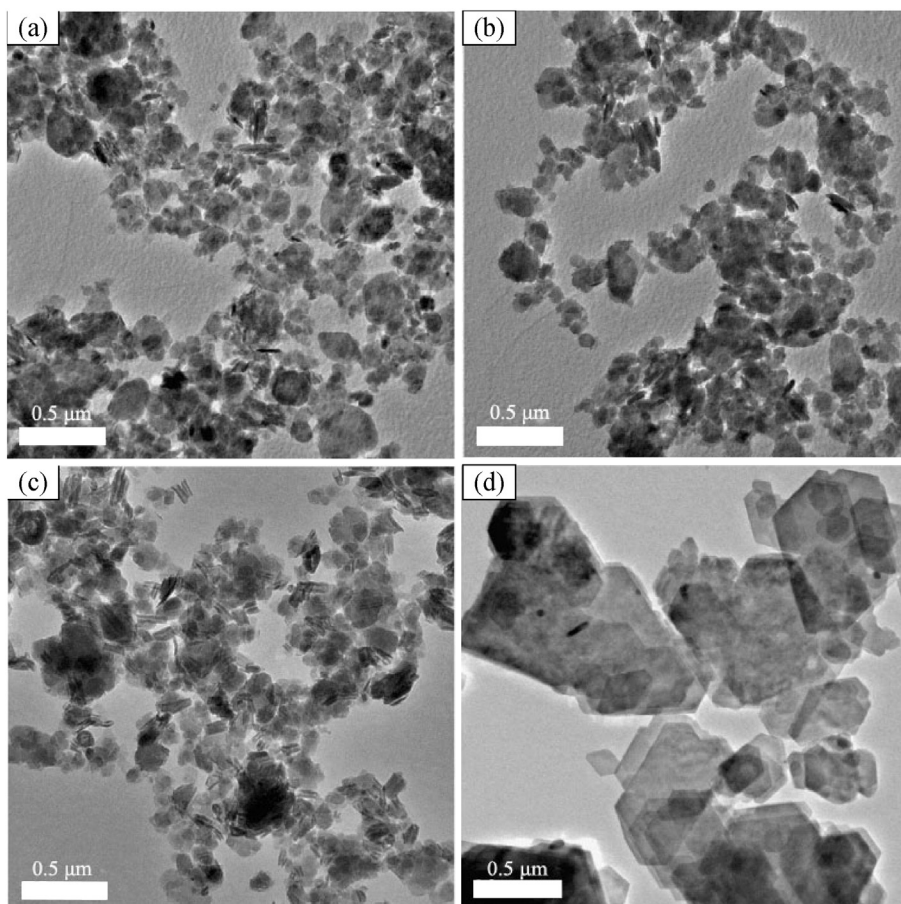
269 Several authors (e.g. Tombácz and Szekeres, 2006) have considered the different natures of the two basal surfaces of kaolin crystals (a hydroxyl surface and on oxygen surface) and the complex edge surfaces. The relative contributions of the different surfaces to CEC are likely to

273 the dependent on crystal size and shape. Their different charge properties of these diverse surfaces and their different susceptibilities to charge variation with changing solution pH will have contributed to the very wide range of CEC values reported for soil kaolin which is illustrated in Fig. 8. It is not possible to identify single values of specific surface area (SSA) and cation exchange capacity (CEC) that can be used to represent the kaolin present in highly weathered topsoil in tropical regions. However, SSA values in the range of  $20\text{--}60 \text{ m}^2 \text{ g}^{-1}$  and CEC values from  $5$  to  $10 \text{ cmol kg}^{-1}$  would seem to be representative of many of the soil kaolins examined by researchers. Values in excess of these numbers might be at least partly due to the presence of impurities and error in measurement. It is clear that industrial and specimen kaolins have SSA and CEC values at the lower limits of these ranges.



**Fig. 5.** (a) Transmission electron microscope images of a kaolin particle from an oxisol. A basally oriented clay aggregate prepared by the ultramicrotome technique shows a section across kaolin plates; (b) High-resolution electron micrographs of the areas in the white rectangles in (a) showing lattice fringes. Fourier Transform (FFT) images of the areas indicated in (b) show that both  $0.7 \text{ nm}$  (kaolin) and  $1.0 \text{ nm}$  (mica) basal spacing minerals are present in this material. Conventional and synchrotron XRDs were unable to detect the  $1.0 \text{ nm}$  mineral (Darunsonontaya et al., 2012).

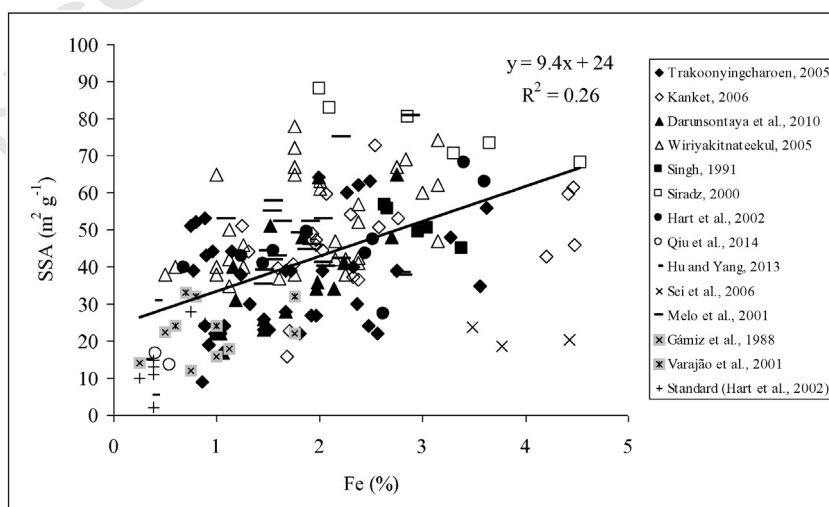
Q1



**Fig. 6.** Transmission electron micrographs of soil kaolins (a) WA169, (b) WA235, (c) IN C63 and (d) Georgia reference kaolin G1261 (Hughes et al., 2009). The much larger crystal size of the mineral kaolin is evident.

286 In addition to the considerable negative charge on the surface of soil  
 287 kaolin crystals that provides cation exchange capacity there are also  
 288 positively charged sites that provide anion exchange (AEC) and anion  
 289 retention (fixation) capacities. As for CEC, the AEC is to some extent  
 290 pH dependent and also the various contributions of crystal edge and  
 291 basal surfaces to CEC and AEC remain uncertain (Khawmee et al.,  
 292 2013). The capacity of soil kaolin to adsorb phosphate is linearly related

293 to the specific surface area (Fig. 9) with kaolins consisting of very small  
 294 crystals ( $SSA\ 80\ m^2\ g^{-1}$ ) being able to retain  $1000\ \mu gP\ g^{-1}$ . For kaolin-  
 295 rich soils, it seems probable that much of the phosphate retention is by  
 296 kaolin rather than by the more reactive but much less abundant  
 297 sesquioxides. Adsorbed phosphate may only be sparingly available to  
 298 plants due to P-fixation by kaolin thereby requiring farmers to apply  
 299 large amounts of fertilizer.



**Fig. 7.** A plot of specific surface area (SSA) versus iron concentration in kaolin from tropical soils. Data from 13 publications. Data for standard kaolins are included.

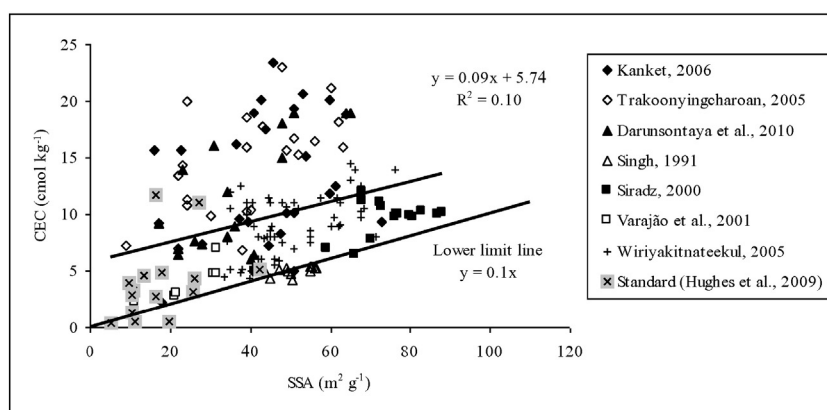


Fig. 8. The non-significant relationship between cation exchange capacity (CEC) and specific surface area (SSA) for kaolin from tropical soils. Data for reference kaolins are included.

#### 4. Soil kaolin in relation to soil fertility

If the kaolin in tropical soils had the large crystal size and associated low surface reactivity of many mineral kaolins, it is likely that the resultant low chemical fertility of the soil would limit agricultural production and the capacity of the soil to cleanse water. Fortunately, soil kaolin has more desirable properties and consequently helps support a large proportion of the world's population (Fig. 1). Fertilizers, lime and organic matter are commonly applied to these soils and reactions of these additives with kaolin crystals enhance soil fertility and structure.

An important and intriguing question for the pedologist and soil mineralogist is why do tropical soils usually contain this type of microcrystalline kaolin in the solum? Parent materials may contain large, perfect kaolin crystals but the overlying solum almost invariably contains microcrystalline, structurally disordered kaolin with structural ferric iron. At present, there is no satisfactory explanation for this phenomenon.

#### Q4 Uncited references

Darunsontaya et al., 2010  
 Gámiz et al., 1988  
 Prasetyo, 1993  
 Sei et al., 2006

#### References

- Borden, D., Giese, R.F., 2001. Baseline studies of the clay minerals society source clays: cation exchange capacity measurements by the ammonia-electrode method. *Clay Clay Miner.* 49, 444–445.
- Brindley, G.W., Brown, G., 1980. *Crystal Structures of Clay Minerals and Their X-ray Identification*. Mineralogical Society, London 495 pp.
- Center for International Earth Science Information Network – CIESIN – Columbia University, 2014. Gridded Population of the World, Version 4 (GPWv4): Population Density, Preliminary Release 2 (2010). (Palisades, NY. <http://www.ciesin.columbia.edu/data/gpw-v4>).
- Chi, M., Eggleton, R.A., 1999. Cation exchange capacity of kaolinite. *Clay Clay Miner.* 47, 174–180.
- Darunsontaya, T., Suddhiprakarn, A., Kheoruenromne, I., Gilkes, R.J., 2010. Geochemical properties and the nature of kaolin and iron oxides in upland oxisols and ultisols under a tropical monsoonal climate, Thailand. *Thai. J. Agric. Sci.* 43, 197–215.
- Darunsontaya, T., Suddhiprakarn, A., Kheoruenromne, I., Prakongkep, N., Gilkes, R.J., 2012. The forms and availability to plants of soil potassium as related to mineralogy for upland oxisols and ultisols from Thailand. *Geoderma* 170, 11–24.
- Dogan, M., Özdemir, Y., Alkan, M., 2007. Adsorption kinetics and mechanism of cationic methyl violet and methylene blue dyes onto sepiolite. *Dyes Pigments* 75, 701–713.
- Gámiz, E., Caballero, E., Delgado, M., Delgado, R., 1988. Characterization of Spanish kaolins for pharmaceutical use: I. Chemical and mineralogical composition, physico-chemical properties. *Boll. Chim. Farm.* 127, 114–120.
- Guggenheim, S., Alietti, A., Drits, V.A., Formoso, M.L.L., Galán, E., Köster, H.M., Paquet, H., Watanabe, T., Bain, D.C., Hudnall, W.H., 1997. Report of the Association Internationale Pour l'Étude des Argiles (Aipea) Nomenclature Committee for 1996. *Clay Clay Miner.* 45, 298–300.
- Hart, R.D., Gilkes, R.J., Siradz, S., Singh, S., 2002. The nature of soil kaolins from Indonesia and Western Australia. *Clay Clay Miner.* 50, 198–207.
- Hart, R.D., Wiriyaakitnateekul, W., Gilkes, R.J., 2003. Properties of soil kaolins from Thailand. *Clay Miner.* 38, 71–94.
- Hillier, S., 2000. Accurate quantitative analysis of clay and other minerals in sandstones by XRD: comparison of a Rietveld and a reference intensity ratio (RIR) method and the importance of sample preparation. *Clay Miner.* 35, 291–302.
- Hu, P., Yang, H., 2013. Insight into the physicochemical aspects of kaolins with different morphologies. *Appl. Clay Sci.* 74, 58–65.
- Hughes, J.C., Gilkes, R.J., Hart, R.D., 2009. Intercalation of reference and soil kaolins in relation to physico-chemical and structural properties. *Appl. Clay Sci.* 45, 24–35.
- ISS Working Group R.B., 1998. World reference base for soil resources: atlas. In: Bridges, E.M., Batjes, N.H., Nachtergaele, F.O. (Eds.), *ISRIC-FAO-ISSS-Acco*. Leuven, Belgium, p. 79.
- Kanket, W., 2006. *Properties of the Clay Fraction of Alfisols and Ultisols in Thailand* Ph.D. Thesis Kasetsart University, Bangkok, Thailand.
- Kanket, W., Suddhiprakarn, A., Kheoruenromne, I., Gilkes, R.J., 2005. Chemical and crystallographic properties of kaolin from ultisols in Thailand. *Clay Clay Miner.* 53, 478–489.
- Kew, G.A., Gilkes, R.J., 2007. Properties of regolith beneath lateritic bauxite in the Darling Range of south Western Australia. *Soil Res.* 45, 164–181.
- Khawme, K., Suddhiprakarn, A., Kheoruenromne, I., Singh, B., 2013. Surface charge properties of kaolinite from Thai soils. *Geoderma* 192, 120–131.
- Melo, V.F., Singh, B., Schaefer, C.E.G.R., Novais, R.F., Fontes, M.P.F., 2001. Chemical and mineralogical properties of kaolinite-rich Brazilian soils. *Soil Sci. Soc. Am. J.* 65, 1324–1333.
- Prasetyo, B.H., 1993. *Chemical, Mineralogical and P-sorption Characteristics of Some Red Soils from West Java* Ph.D. Thesis The University of Western Australia, Perth, Australia.
- Qiu, X., Lei, X., Alshameri, A., Wang, H., Yan, C., 2014. Comparison of the physicochemical properties and mineralogy of Chinese (Beihai) and Brazilian kaolin. *Ceram. Int.* 40, 5397–5405.
- Retallack, G.J., 1990. *Soils of the Past: An Introduction to Palaeopedology*. Kluwer Academic Publishers, London, p. 520.

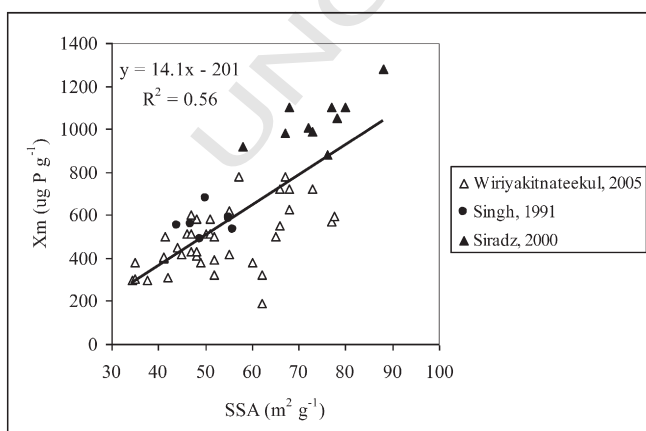


Fig. 9. The Langmuir maximum P retention capacity ( $X_m$ ) of kaolin from tropical soils as a function of specific surface area (SSA).



- 382 Sei, J., Morato, F., Kra, G., Staunton, S., Quiquampoix, H., Jumas, J.C., Olivier-Fourcade, J.,  
383 2006. Mineralogical, crystallographic and morphological characteristics of natural kaolins  
384 from the Ivory Coast (West Africa). *J. Afr. Earth Sci.* 46, 245–252.
- 385 Singh, B., 1991. Mineralogical and Chemical Characteristics of Soils from South-western  
386 Australia Ph.D. Thesis The University of Western Australia, Perth, Australia.
- 387 Singh, B., Gilkes, R.J., 1991. Weathering of a chromian muscovite to kaolinite. *Clay Clay*  
388 *Miner.* 39, 571–579.
- 389 Singh, B., Gilkes, R.J., 1995. Application of analytical transmission electron microscopy to  
390 identifying intercrystal variations in the composition of clay minerals. *Analyst* 120,  
391 1335–1339.
- 392 Siradz, S., 2000. Mineralogy and Chemistry of Red Soils of Indonesia Ph.D. Thesis The Uni-  
393 versity of Western Australia, Perth, Australia.
- 394 St. Pierre, T.G., Singh, B., Webb, J., Gilkes, R.J., 1992. Mössbauer spectra of soil kaolins from  
395 south-western Australia. *Clay Clay Miner.* 40, 341–346.
- 396 Stucki, J.W., 2006. Chapter 8. Properties and behaviour of iron in clay minerals. *Handbook*  
397 *of Clay Science* Developments in Clay Science. Elsevier, pp. 423–475.
- Tawornpruek, S., Kheoruenromne, I., Suddhiprakarn, A., Gilkes, R.J., 2006. Properties of red  
398 oxisols on calcareous sedimentary rocks in Thailand. *Geoderma* 136, 477–493. 399
- Tombác, E., Szekeres, M., 2006. Surface charge heterogeneity of kaolinite in aqueous sus-  
400 pension in comparison with montmorillonite. *Appl. Clay Sci.* 34, 105–124. 401
- Trakoonyingcharoen, P., 2005. The Nature of Red Oxisols and Red Ultisols in Thailand  
402 Ph.D. Thesis Kasetsart University, Bangkok, Thailand. 403
- Trakoonyingcharoen, P., Kheoruenromne, I., Suddhiprakarn, A., Gilkes, R.J., 2006. Proper-  
404 ties of kaolins in red oxisols and red ultisols in Thailand. *Appl. Clay Sci.* 32, 25–39. 405
- Van Olphen, H., Fripiat, J.J., 1979. *Data Handbook for Clay Minerals and Other Non-*  
406 *metallic Minerals.* Pergamon Press, Oxford, England, p. 346. 407
- Varajão, A.F.D.C., Gilkes, R.J., Hart, R.D., 2001. The relationships between kaolinite crystal  
408 properties and the origin of materials for a Brazilian kaolin deposit. *Clay Clay*  
409 *Miner.* 49, 44–59. 410
- Wiriyakitnateekul, W., 2005. The Properties of Clays in Red and Yellow Soils of Thailand  
411 Ph.D. Thesis Kasetsart University, Bangkok, Thailand. 412
- Young, A., 1976. *Tropical Soils and Soil Survey.* University Press, Cambridge, p. 468.

UNCORRECTED PROOF