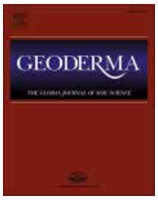
Geoderma 470 (2026) 117832

Contents lists available at ScienceDirect

Geoderma

journal homepage: www.elsevier.com/locate/geoderma



Systematic review and meta-analysis

Occurrence of 2:1 phyllosilicates in Ferralsols: A viewpoint

Ary Bruand [a], Michel Brossard [b], Laurent Caner [c]

[a] Institut des Sciences de la Terre d'Orléans (ISTO), UMR 7327, UO - CNRS - BRGM, Observatoire des Sciences de l'Univers en région Centre (OSUC), Université d'Orléans, 1A rue de la Férollerie, 45071 Orléans, Cedex 2, France

[b] Institut de Recherche pour le Développement (IRD), Eco&Sols, UMR IRD – INRAE – CIRAD – Institut Agro – Université de Montpellier, Campus Gaillarde, Institut Agro-INRAE, 2 place Viala, 34060 Montpellier, Cedex 2, France

[c] Institut de Chimie des Milieux et Matériaux de Poitiers (IC2MP Hydrasa), UMR 7285, CNRS – Université de Poitiers, 4 rue Michel Brunet, 86073 Poitiers, Cedex 9, France

ARTICLE INFO

Handling Editor: Dr Alberto Agnelli

Keywords:
Tropical soil
Ferrallitic soil
Latosol
Oxisol
Ferralisol
Ferrosol
Ferrallisol
Mica
Illite
Vermiculite
Hydroxy-Al interlayered vermiculite (HIV)
Smectite
Hydroxy-Al interlayered smectite (HIS)
Biological activity
Termite

ABSTRACT

In the humid tropics, Ferralsols can be considered as being the end of a geochemical sequence of weathering. Easily weatherable primary minerals should then have completely disappeared; consequently, their fine fraction which is largely dominated by low-activity clay minerals, and aluminum and iron sesquioxides. However, the occurrence of small amounts of 2:1 phyllosilicates has been recorded in many Ferralsols. Since the presence of these minerals in these intensively weathered soils has never been the subject of a comprehensive study, we conducted an analysis of the literature from the past sixty years. This has shown that, since the first studies, most of the 2:1 phyllosilicates recorded in Ferralsols have been identified solely by X-ray diffraction, thanks to a peak at approximately 1.4 nm that did not expand upon solvation with ethylene glycol and became a broad peak between 1.2 and 1.0 nm when heated to 300°C. These XRD features are similar to those observed for 2:1:1 phyllosilicates with incomplete Al-hydroxy interlayering. The name given to these minerals has evolved over the years as knowledge about phyllosilicates advanced. It was shown that these 2:1 phyllosilicates, often interpreted as hydroxy-Al interlayered minerals, were mainly present in the fine-silt and coarse-clay fraction. They were found in Ferralsols of the South-American, African and Asian intertropical zones. Although their possible presence in very small proportions has gradually been integrated into the definition of Ferralsols or equivalent soils according to the soil classification systems used, their origin remains debated. While some authors interpret them as resulting from neoformation processes within the soil or as being relict minerals that have resisted weathering processes, a growing number of authors interpret their presence, without calling into question the two previous hypotheses, as resulting from soil the mixing of by the by activity of social soil insects, in particular that of termites. It is hypothesized that material transported from the saprolite seeded the entire Ferralsol profile with 2:1 phyllosilicates, formed either through neogenesis or primary mineral weathering. These minerals remain observable today where soil fauna have redistributed them, and undergo aluminization and desilication consistent with the geochemical context to which they are exposed. Finally, studies on the availability of potassium potentially present in the interlayer space of the 2:1 phyllosilicates indicate that 5 to 30% of this potassium can be exchangeable when the Ferralsols considered are still under native vegetation. Once cultivated, this reserve of exchangeable potassium reserve is depleted within a few years, and subsequent annual inputs from the remaining potassium stock are very low.

1. Introduction

Many deeply weathered red or yellow soils in the humid tropics are Ferralsols (IUSS Working Group WRB, 2022). They may correspond to Oxisols, or some LAC Ultisols and Alfisols in the Soil Taxonomy (Soil Survey Staff, 2006), to Latosols in the Brazilian soil classification (Embrapa, 2006), mainly to Ferrallisols in the Genetic Soil Classification of China and to Ferrosols in the Chinese Soil Taxonomy (Shi et al., 2004; 2006), and to Ferrallitic soils in the French soil classification system (Commission de Pédologie et Cartographie des Sols, 1967) and to Ferrallitisols in the French Référentiel Pédologique (AFES, 2009). They represent a large land surface area of 750 million hectares worldwide (IUSS Working Group WRB, 2022), which corresponds in the tropics to about 14% of the land surface area. They are mostly located in South America, Africa and Asia (FAO-UNESCO, 1974). They result from a very long sequence of intense weathering under conditions that have prevailed for hundreds of thousands of years, even millions of years in some areas (Eswaran and de Conninck, 1971; Van Wambeke et al., 1983; Van Wambeke, 1992; Schaefer and Delrymple, 1995; Scholten et al., 1997; Buol and Eswaran, 1999; IUSS Working Group WRB, 2022; Zech et al.,

https://doi.org/10.1016/j.geoderma.2026.117832
Received 2 October 2025; Received in revised form 24 April 2026; Accepted 26 April 2026

2022). They can be considered as corresponding to a possible end of a geochemical sequence of weathering (Pédro, 1968; Melfi and Pédro, 1977; Van Wambeke et al., 1983). The result is that easily weatherable primary minerals, such as ferromagnesian minerals and glasses, as well as more resistant minerals such as micas and feldspars, are considered to have completely disappeared (Buringh, 1970; Van Wambeke, 1992). Consequently, their fine fraction is largely dominated by low-activity clay minerals such as kaolinite, and aluminum and iron sesquioxides (gibbsite, goethite and haematite) (Pédro, 1968; Melfi and Pédro, 1977; 1978; Zech et al., 2022) in varying proportions depending on the parent material and landscape position (Curi and Franzmeier, 1984; Macedo and Bryant, 1987; Ker, 1997; Reatto et al., 2000, 2008, 2010; Schaefer et al., 2008; Nakao et al., 2017).

However, the occurrence of 2:1 phyllosilicates has been reported in many Ferralsols or their equivalent in other soil classifications (e.g. Moniz, 1967; Moura Filho and Buol, 1972; Escobar et al., 1973; Poss et al. 1991; Kämpf et al., 1995; Azevedo et al., 1996; Scholten et al., 1997; Melo et al., 2004; He et al., 2008; Maquere, 2008; Perreira et al., 2010; Inda et al., 2010; Caner et al., 2014; Darunsontaya et al., 2010; 2012; Khawmee et al., 2013; Mujinya et al., 2013; Nakao et al., 2017, Bertolazi et al., 2017; de Oliveira et al., 2020; Volf et al., 2023) to the point that their presence is mentioned in the World Reference Base for Soil Resources (IUSS Working Group WRB, 2022). In this document, the definition of the ferralic horizon mentions the possible presence of weatherable minerals such as 2:1 phyllosilicates in the 50–200 μm fraction if the total content in weatherable minerals is smaller than 10% by grain count. The weatherable minerals include minerals that are highly unstable in the humid tropics compared to quartz, 1:1 clay minerals and oxy-hydroxides, and more resistant than calcite (IUSS Working Group WRB, 2022). The Soil Taxonomy (Soil Survey Staff, 2006) also mentioned the possible presence in the oxic horizon of hydroxy-Al interlayered vermiculites in the clay fraction and of weatherable minerals in the 50–200 μm if they do not exceed 10% (Herbillon, 1980). In the Brazilian soil classification (Embrapa, 2006), although Latosols are described as thick to very thick soils resulting from intense weathering of minerals present in parent materials, muscovite can be found in small amounts in the coarse fraction of the Bw horizon, whereas silt and clay fractions may contain very small amounts of 2:1 phyllosilicates such as illite and smectite (Herbillon, 1980). The possible presence of 2:1 phyllosilicates such as illite or weathered vermiculite in small quantities is also mentioned in the French Référentiel Pédologique (AFES, 2009).

While the World Reference Base for Soil Resources (IUSS WRB, 2022) and other classification systems (Soil Survey Staff, 2006; Embrapa, 2006; AFES, 2009) acknowledge that Ferralsols may contain small amounts of weatherable minerals like 2:1 phyllosilicates, without requiring this presence as a diagnostic criterion for classification, their origin in these intensely weathered soils is rarely addressed, despite being well documented. How can such minerals be present in soils resulting from a long sequence of intense weathering under conditions that have prevailed for hundreds of thousands of years in the humid tropics? The very wide diversity of 2:1 phyllosilicates described by the various authors also raises questions. How can 2:1 phyllosilicates such as micas, interstratified clay minerals, vermiculites and smectites still be present? In this context, our objective was to discuss: (i) the studies conducted over the last sixty years that identified 2:1 phyllosilicates in Ferralsols, (ii) the gradual integration of their presence into the definition of Ferralsols (IUSS Working Group WRB, 2022) or their equivalent in other soil classifications, (iii) the characteristics of the Ferralsols where 2:1 phyllosilicates have been identified, (iv) the characteristics of the 2:1 phyllosilicate particles, (v) the hypotheses explaining their presence in these deeply weathered soils, and finally (vi) the consequences of their presence for soil properties.

2. Presence of 2:1 phyllosilicates in Ferralsols

2.1. Early studies showing the presence of 2:1 phyllosilicates

Early studies showing the presence of 2:1 phyllosilicates in Ferralsols or related soils were conducted during the 1960 s and 1970 s in Brazil (Table 1). Moniz (1967), for example, showed the presence of 2:1 phyllosilicates in the clay fraction of Brazilian Oxisols developed on mafic parent material and slate. The presence of 2:1 phyllosilicates in Ferralsols was also mentioned early by Buringh (1970), who noted, in his introduction to the study of soils in tropical and subtropical regions, the presence of traces of weatherable minerals in the B horizon of Ferrallitic soils, but without any further comment. Moura Filho and Buol (1972) studied the mineralogy of the clay fraction of the topsoil horizon of a Ferralsol developed on mafic rocks identified as a Red Latosol. Using X-ray diffraction (XRD), they showed the presence of 2:1 phyllosilicates in the < 2 μm fraction named “*intergradational material*” by the authors and characterized by a peak at 1.45 nm. This peak did not expand upon solvation with ethylene glycol and became a broad peak between 1.2 and 1.0 nm when heated to 350°C. According to the authors, this behavior suggested the presence of hydroxy-aluminum in the interlayer space of particles of 2:1 phyllosilicates. Thus, the presence of these minerals which were frequently referred to as hydroxy-Al interlayered vermiculite (HIV) was established from the earliest studies and confirmed in numerous Ferralsols over the following decade (Moura Filho and Buol, 1972). Then, Cline and Buol (1973) studied Ferralsols of the Central Plateau of Brazil and mentioned the presence of traces of “*2:1/2:2 interlayered mineral*” in the < 2 μm fraction of horizons A and B of a Dark Red Latosol. Escobar et al. (1973) studied two Brazilian Ferralsols identified as a Dark Red Latosol and a Red Latosol, both developed on igneous basic rocks and showed using XRD the presence of 2:1 phyllosilicates in very small quantities in the clay fraction. They were identified as being mica and vermiculite owing to the presence of peaks at approximately 1.0 and 1.4 nm, respectively. They were present in horizons A, B and C of the two Ferralsols studied by Escobar et al. (1973). Although it was not discussed by the authors, the results presented did not allow for a distinction between the presence of vermiculite or HIV. Furthermore, the presence of mica did not appear clearly on the X-ray diffractograms. Weaver (1974) studied the chemical and mineralogical properties of Red Latosols or Red-Yellow Latosols. Using XRD, he also found traces of 2:1 phyllosilicate in the < 2 μm fraction identified as mica and vermiculite due to the presence of peaks at 1.0 nm and 1.4 nm, respectively. The asymmetry of the peak at 1.0 nm and the behavior of the peak at 1.4 nm upon heating were interpreted as interstratification between mica and vermiculite, the latter having an interlayer space partly occupied by hydroxy aluminum and was later named hydroxy-Al interlayered vermiculite (HIV).

During the same years, other studies highlighted the presence of 2:1 phyllosilicates in African Ferralsols classified as Udox in the Oxisol order (Table 1). Le Roux (1973) showed the presence of a clay mineral that he called “*pedogenic aluminous chlorite*” corresponding to a well-defined peak at 1.4 nm on the X-ray diffractograms. He also identified mica in trace amounts with a weak peak at 1.0 nm on some of the X-ray diffractograms. Combining thermal analyses and chemical analyses, Le Roux (1973) found that chlorite and mica contents ranged from 20 to 30% and from 10 to 20% of the < 2 μm fraction after sesquioxide removal, respectively. These values, which appear to be high, were estimated based on numerous hypotheses and should therefore be considered as a rough estimation. Then, Fey (1974) studied A and B horizons of four other South African Ferralsols classified as Oxisols. Using XRD, he also showed the presence of 2:1 phyllosilicates that were identified as being mainly “*pedogenic aluminous chlorite*” and secondarily as mica. Based on the same hypotheses as those used by Le Roux (1973) and with the same methodological limits, Fey (1974) found that the chlorite and mica contents ranged from 5.9 to 20.9% and from 3.3 to 14.1% of the < 2 μm fraction after sesquioxide removal, respectively. In

Table 1
Studies in which 2:1 phyllosilicates were recorded in Ferralsols (IUSS Working Group WRB, 2022) or in their equivalent according to other soil classifications, as named by the authors in the studies.

Authors	Country	Soil type	Depth[a] (cm)	2:1 Phyllosilicates[b]			Method
				Sand	Silt	Clay	
Moniz (1967)	Brazil	Oxisol	–	–	–	Mi, V	XRD
Moura Filho and Buol (1972)	Brazil	Latosol	0–20	–	–	IM	XRD
Cline and Buol (1973)	Brazil	Latosol	0–60	–	–	2:2/2:2 IM	XRD
Escobar et al. (1973)	Brazil	Latosol	–	–	–	M, V	XRD
Boyer (1973)	CAR[e]	Ferralitic soil	–	–	–	Ill	XRD
Le Roux (1973)	South Africa	Oxisol	0–180	–	–	M, V, Mt, P-A-Chl	XRD, TA, CA
Fey (1974)	South Africa	Oxisol	0–240	–	–	P-A-Chl	XRD, TA, CA
Lepsch and Buol (1974)	Brazil	Oxisol	0–200	–	–	Mi, V, Int-Chl-V	XRD
Weaver (1974)	Brazil	Latosol	0–60	–	–	Mi, Chl	XRD
Ogawa et al. (1981)	Thailand	Latosol	0–25	–	–	Al-V	XRD
Jones et al. (1982)	Puerto Rico	Ferralsol	0–130	Chl	Chl	Chl	XRD, TEM
Santana (1984)	Brazil	Oxisol	100 and 300	–	–	HIV	XRD
Arkcoll et al. (1985)	Brazil	Oxisol	0–140	–	–	Ill, Sm	XRD, CA, MC
Eschenbrenner (1986)	Ivory Coast	Ferralitic soil	–	–	Mu, Ill	–	XRD
Kalima and Spaargaren (1987)	Zambia	Oxisol	–	–	–	Mi, V, I-V	XRD
Antonello (1988)	Brazil	Oxisol	70–290	–	–	Mi, HIV	XRD
Muchena and Wokabi (1988)	Kenya	Ferralsol	–	–	–	Ill	XRD
Møberg and Esu (1991)	Nigeria	Oxisol	5 – 160	Mi	Chl-K	Ill, V-Chl	XRD
Poss et al. (1991)	Togo	Ferralsol	0–100	–	–	Int-Ill-Sm	XRD, TEM, CA
Sanz-Scovino et al. (1992)	Colombia	Oxisol	0–100	HIV	M, HIV	HIV	XRD
Kampf et al. (1995)	Brazil	Latosol	–	–	–	HIS	XRD, MS
Azevedo et al. (1996)	Brazil	Latosol	0–80	–	–	HIS	XRD
Brito Galvão and Schulze (1996)	Brazil	Oxisol	0–195	–	Mi	HIV	XRD, TEM
Scholten et al. (1997)	Swaziland	Ferralsol	0–200	–	Mi	Ill	XRD
Vidal-Torrado and Lepsch (1999)	Brazil	Latosol	70–80	–	–	Mi, V, HIV	XRD
Vidal-Torrado et al. (1999)	Brazil	Latosol	94–850	–	–	Mi, V, HIV	XRD
Caner et al. (2000)	India	Lateritic parent material	80–100	–	–	Mi, HIV	XRD
Mafra et al. (2002)	Brazil	Latosol	0–120	–	–	Int-Ill-V, V	XRD
Martins et al. (2004)	Brazil	Latosol	0–40	–	Mi, Chl	Mi, Chl	XRD
Melo et al. (2004)	Brazil	Latosol	30–240	–	–	Mi	XRD
Oliveira et al. (2004)	Brazil	Latosol	0–190	–	–	HIV[c]	XRD
Zhang et al. (2004)	China	Latosol, Lateritic red soil	–	–	–	V, Ill	XRD
Soares et al. (2005)	Brazil	Oxisol	0–130	–	Mi, Ill	HIV[c]	XRD-EDS
Dowding and Fey (2007)	South Africa	Oxisol	0–110	–	–	Chl, Mi	XRD
He et al. (2008)	China	Ferralsol	–	–	–	V	XRD
Maquere (2008)	Brazil	Latosol	0–300	–	–	HIV	XRD
Rolim Neto et al. (2009)	Brazil	Latosol	0–200	–	–	Ill, HIV	XRD
Ryan and Huertas (2009)	Costa Rica	Oxisol	0–180	–	–	Sm-K	XRD, TEM, FTIR
Darunsontaya et al. (2010)	Thailand	Oxisol	0–30	–	–	Ill, V	XRD, TEM, TEM-EDS
Inda et al. (2010)	Brazil	Oxisol	0–3	–	–	HIV	XRD
Pereira et al. (2010)	Brazil	Latosol	–	–	Mu	Ill, HIV	XRD
Reatto et al. (2010)	Brazil	Ferralsol	60–200	–	–	HIV	XRD
Caner et al. (2011)	India	Lateritic parent material	55–85	–	–	HIV[f]	XRD
Marques et al. (2011)	Brazil	Latosol	0–120	–	–	HIV	XRD
Darunsontaya et al. (2012)	Thailand	Oxisol	0–30	–	–	Ill, HIV	XRD, TEM, TEM-EDS, EFTEM
Alves et al. (2013)	Brazil	Latosol	4–160	Mi	Mi	Mi-M	XRD
Dias et al. (2013)	Brazil	Ferralsol	0–20	–	–	V	XRD-RM
Khawmee et al. (2013)	Thailand	Oxisol	15–55	–	–	Ill, HIV	XRD
Mujinya et al. (2013)	D.R. Congo	Ferralsol	0–500	–	–	Mi, Ch, Sm, Ml	XRD
Paisani et al. (2013)	Brazil	Oxisol	0–930	–	–	HIV	XRD
Caner et al. (2014)	Brazil	Ferralsol	0–190	–	–	HIM, HIS	XRD, CE, FTIR
Jouquet et al. (2016	India	Ferralsol	0–10	–	–	Ill, Sm, Tc	XRD
Bertolazi et al. (2017)	Brazil	Oxisol	0–40	–	–	V, HIM	XRD
Nakao et al. (2017)	Cameroon	Ferralsol	2–65	–	–	Ill, HIV	XRD
Cunha et al. (2017)	Brazil	Latosol	89–122	–	–	Mi[c], HIV[c] (Fig. 2)	XRD
Pinctus et al. (2017)	Costa Rica	Oxisol	5–200	–	–	Sm-K	XRD, TEM, FTIR
Testoni et al. (2017)	Brazil	Oxisol	–	–	–	IKS, HIS	XRD
Pacheco et al. (2018)	Brazil	Latosol	38–70	–	–	V, HIV	XRD
Cunha et al. (2019)	Brazil	Latosol	0–220	–	–	Mi, Int-Mi-HIV	XRD
Korchagin et al. (2019)	Brazil	Ferralsol	0–50	–	–	HIV	XRD
Ndzana et al. (2019)	China	Oxisol	0–80	–	–	Ill, Int-Ill-V, HIV	XRD, FTIR, TG
Costa et al. (2020)	Brazil	Latosol	0–20	–	–	Ill, Sm, SHI	XRD
Firmano et al. (2020)	Brazil	Oxisol	0–40	–	–	2:1 CM	XRD
Oliveira et al. (2020)	Brazil	Ferralsol	0–20	–	–	Mi, 2:1 CM	XRD
Almeida et al. (2021)	Brazil	Latosol	0–70	Mi	Mi	Ill, HIV	XRD
Mancini et al. (2021)	Brazil	Oxisol	0–450	–	Mu[c]	–	XRD
Silva et al. (2021)	Brazil	Oxisol	0–100	Mi	Mi	HIV[c]	XRD
Bruand and Reatto (2022)	Brazil	Ferralsol	115–200	–	WMu	WMu, HIV	BESI, SEM-EDS
Bruand et al. (2022)	Brazil	Ferralsol	100–200	WMu	WMu, HIV	WMu, HIV	BESI, SEM-EDS
Souza Lopes et al. (2022)	Brazil	Ferralsol	25–120	–	–	Ill	DRX
Bruand et al. (2023)	Brazil	Ferralsol	60–200	WMu	WMu, HIV	WMu, HIV	BESI, SEM-EDS
Chiapini et al. (2023)	Brazil	Ferralsol	0–769	–	–	HI	DRX

(continued on next page)

Table 1 (*continued*)

Authors	Country	Soil type	Depth[a] (cm)	2:1 Phyllosilicates[b] Sand	Silt	Clay	Method
Volf et al. (2023)	Brazil	Ferralsol	0–40	–	Mi	Ill, Int-Ill-HIV, HIV	XRD
Bruand et al. (2024)	Brazil	Ferralsol	60–200	WMu	WMu, HIV	WMu, HIV	BESI, SEM-EDS, CA
Hummes et al. (2024)	Brazil	Ferralsol	0–20	–	–	Mi, Ill, HIV	XRD
Li et al. (2024)	China	Oxisol	0–40	–	–	Chl, V, Ill	XRD
Ryan et al. (2024)	Costa Rica	Oxisol	0–180	–	–	Sm-K	XRD, TEM, FTIR
Silva et al. (2024)	Brazil	Oxisol	20–80	Mu	Mu	Mu, 2:1 CM	XRD

Al-V: Aluminum Vermiculite; Chl-K: chlorite-kaolinite; HI: Hydroxy interlayered 2:1 clay minerals; Chl: Chlorite; CM: 2:1 Clay minerals; HIS: Hydroxy interlayered smectite; HIV: Hydroxy-Al interlayered vermiculite; IGM: Intergradational material; IKS: Interstratified kaolinite-smectite; Ill: Illite; Int-Chl-V: Interstratified Chlorite-Vermiculite; Int-Ill-Sm: Interstratified Illite-Smectite; Int-Ill-V: Interstratified Illite-vermiculite; Int-Mi-HIV: Interstratified Mica-Hydroxy-Al interlayered vermiculite; I-V: Interlayered-Al Chlorite; Mi: Mica; Ml: Mixed-layer clays; Mi-M: Micaceous minerals; Mt: Montmorillonite; Mu: Muscovite; P-A-Chl: Pedogenic Aluminous Chlorite; Sm: Smectite; Sm-K: smectite-kaolinite; SHI: Smectite with Al-hydroxy-interlayered; Tc: Talc; V: Vermiculite; V-Chl: vermiculite-chlorite; WMu: Weathered muscovite; 2:1, 2:2/2:2 IM: 2:2/2:2 interlayered mineral.

BESI: Backscattered electron scanning images; CA: Chemical analysis; CE: Chemical extraction; EFTEM: Energy filtered transmission electron microscopy; FTIR: Fourier-transform infrared spectroscopy; MC: Microcalorimetry; MS: Mössbauer spectrometry; SEM-EDS: Scanning electron microscopy with energy dispersive spectrometry; TA: Thermal analysis; TEM: Transmission electron microscopy; TEM-EDS: Transmission electron microscopy with energy dispersive analysis of X-rays; TG: Thermogravimetric analysis; XRD: X-Ray diffraction; XRD-RM: X-Ray diffraction with Rietveld method;

[a] : Depth at which 2:1 phyllosilicates were recorded; [b]Named as in the text published; [c]: Not in text published but identified on the XRD curves published; [d]: identified on XRD but not discussed in the text; [e]: Central African Republic; [f]: Powder X-ray diffraction patterns of the < 2 mm fraction.

a later study on exchangeable potassium in South African soils, including the Ferralsols studied by Le Roux (1973) and Fey (1974), Farina and Le Roux (1974) mentioned the presence of mica and vermiculite without however specifying that it was probably HIV, abandoning the use of the term "*pedogenic aluminous chlorite*".

Studies continued in Brazil with the work of Lepsch and Buol (1974) on Brazilian Oxisols located in a Oxisol-Ultisol toposequence (Table 1). They showed the presence in trace amounts of mica, vermiculite, and interstratified chlorite-vermiculite in the clay fraction of the A and B horizons from the surface down to 140 cm depth. The presence of a peak at 1.41 nm on the diffractogram of the fine clay (< 0.2 μm) and a peak at 1.48 nm in coarse clay (0.2–2 μm), was particularly clear, while the peak at 1.0 nm indicating the presence of mica was very discreet. The behavior of the peaks at 1.41 and 1.48 nm after solvation with ethylene glycol and upon heating indicated that the 2:1 phyllosilicates present could be HIV. The chemical and mineralogical properties of six Brazilian Ferralsols among the Ferralsols studied by Cline and Buol (1973) and identified as Dark Red Latosol or Red-Yellow Latosol (Embrapa, 2006) were studied in detail by Weaver (1974). He observed a peak at 1 nm and another peak at 1.4 nm on the X-ray diffractograms which collapsed readily upon heating. These peaks were interpreted as indicating the presence of mica and vermiculite, respectively, in the three Red-Yellow Latosols studied. Mica and vermiculite contents were estimated as representing not more than 5–10% of the clay fraction. Highly weathered tropical soils of Puerto Rico in the Caribbean, including several Oxisols, were studied by Beiroth (1982), Jones et al. (1982) and Fox (1982). Using X-ray diffraction and transmission electron microscopy, Jones et al. (1982) demonstrated the presence of 2:1 phyllosilicates in the clay, silt, and fine sand fractions, identified as chlorite due to the presence of a peak at 1.44 nm that does not expand with ethylene glycol. Data concerning heating behavior were lacking, and published data on Ultisols studied in the same environment suggest that it was HIV. Arkcoll et al. (1985), working on the clay mineralogy of Oxisols in the Manaus region (Brazil), using X-ray diffraction showed the presence of trace amounts of 2:1 phyllosilicates in the clay fraction, mainly illite (1–3%) and smectite (1–2%).

During the international soil classification workshop held in 1986 in Brazil and dealing with the classification, characterization and utilization of Oxisols, Antonello (1988) presented the mineralogy of the clay fraction of 23B horizons collected from 70 to 290 cm depth in Oxisols located in different Brazilian states. HIV was observed in 52% of the horizons studied and mica in 30% of them. During this workshop, Herbillon (1988) addressed the question of the presence of weatherable minerals in the diagnostic horizons of low-activity clay soils and its consequences for the "*total reserve in bases (TRB)*". Muscovite content in the coarse fraction was estimated to reach up to 6% by mass in oxic horizons (Herbillon, 1980; 1988).

2.2. Proliferation of studies showing the presence of 2:1 phyllosilicates during the past three decades

During the years which followed, there was a proliferation of studies showing the presence of 2:1 phyllosilicates in trace amounts in the A and B horizons of Ferralsols (Table 1). Numerous studies in the last three decades have shown the presence of 2:1 phyllosilicates in many Brazilian Ferralsols (e.g. Kämpf et al., 1995; Azevedo et al., 1996; Melo et al., 2004; Maquere, 2008; Perreira et al., 2010; Inda et al., 2010; Caner et al., 2014; Bertolazi et al., 2017; de Oliveira et al., 2020; Volf et al., 2023; Reatto et al., 2010; Chiapini et al., 2023; Bruand et al., 2023; 2024). In his review of Brazilian Latosols, Ker (1997) mentioned the presence of 2:1 phyllosilicates identified as illite, vermiculite and hydroxy-Al-interlayered-vermiculite in their clay fraction.

Several studies have concerned Ferralsols in Central America. Using X-ray diffraction, transmission electron microscopy and Fourier transform infrared spectroscopy, Ryan and Huertas (2009), Pincu et al. (2017) and Ryan et al. (2024) studied chronosequences of tropical soils in Costa Rica developed from basaltic-andesitic parent material. They showed the presence of smectite, hydroxy-Al interlayered smectite (HIS) and interstratified smectite/kaolinite in Oxisols aged from 30,000 to 120,000 years.

The presence of 2:1 phyllosilicates has also been shown in Asian countries such as Thailand (Darunsontaya et al., 2010; 2012; Khawmee et al., 2013), China (He et al., 2008), as well as India (Jouquet et al., 2016a; 2016b). However, the number of studies showing the presence of 2:1 phyllosilicates in Asian Ferralsols appears to be limited.

Some studies have concerned Ferralsols in African countries such as Togo (Poss et al., 1991), Swaziland (Scholten et al., 1997), Democratic Republic of Congo (Mujinya et al., 2013) and Cameroon (Nakao et al., 2017). Muchena and Wokabi (1988), describing the major characteristics of Kenyan red soils, mentioned the presence of traces of illite in the < 2 μm fraction of several Ferralsols without further details. Poss et al. (1991), studying potassium release and fixation in Togolese Ferralsols, showed the presence of 1.4 to 2.1% of 2:1 phyllosilicates identified as interstratified clay minerals using XRD. The weak intensity of the peak at 1.4 nm on the X-ray diffractograms restricted the discussion about the possible swelling after solvation by glycerol and its consequences for the presence of vermiculite or smectite clay minerals. However, observations in transmission electron microscopy showed that expanded interlayer spaces were located at the edges of mica particles, which is consistent with the weathering of mica by particle ends.

2.3. Presence of 2:1 phyllosilicates in the definition of Ferralsols and their equivalent depending on the soil classification used

Given the significant number of studies showing the presence of easily weatherable minerals in Ferralsols or in their corresponding soils in other soil classifications, the possible presence of such minerals was integrated early into the definition of the characteristics of these soils within the soil classifications but without their presence becoming a taxonomic criterion. Thus, from 1974, the presence of traces of primary minerals such as feldspar, mica or ferro-magnesian minerals was mentioned in the legend of the Soil Map of the World published in 1974 (FAO-UNESCO, 1974) for the oxic B horizon, which became the ferralic B horizon in the following editions. In the revised legend of the Soil Map of the World (FAO, 1988), the possible presence of weatherable minerals was mentioned for the 50–200 µm fraction in the ferralic B horizon if their presence did not exceed 10 percent. This possible presence of weatherable minerals in the 50–200 µm fraction was repeated identically in the statement of the properties of the ferralic horizon in the first version of the World Reference Base for Soil Resources (ISSS-IRSIC FAO, 1988).

In the 1975 edition of the Soil Taxonomy (Soil Survey Staff, 1975), the possible presence of easily alterable minerals did not appear in the main text defining the properties of the Oxic horizon. The latter is described as consisting of "*a mixture of hydrated oxides of iron or aluminum, or both, with variable amount of 1:1 lattice clay*". It should nevertheless be noted that in a footnote, it was indicated that "*recent studies on Oxisols and other old soils suggest that one 2:1 lattice clay either is extremely resistant to weathering in a humid climate, perhaps more so than kaolin, or has formed from dust that accumulates slowly over the millennia. This is an Al-interlayered chlorite. It has a 14Å reflection but will not collapse to 10 Å on potassium saturation and heating. It is commonly present in oxic horizons in at least a moderate amount, but the amount decreases with depth.*" In 1977, the Soil Conservation Service established the International Committee on Oxisols (ICOMOX) to review the classification of Oxisols and make recommendations for changes. The question of the presence of weatherable minerals in the Oxic B horizon was discussed during the different meetings between 1978 and 1986, leading to a proposed amendment specifying that the Oxic B horizon "*does not have as much as 10 percent weatherable minerals in the 50——200 µm fraction*" (ICOMOX, 1988). This amendment was presented during the Eighth International Soil Classification Workshop on Oxisols held in Brazil in 1986 (ICOMOX, 1988) and the possible presence of weatherable minerals was added to the properties of the Oxic B horizon of the Soil Taxonomy (Soil Survey Staff, 1998 and 1999). Note that only weatherable minerals represented by grains ranging from 50 to 200 µm in diameter were mentioned, whereas most studies having shown the presence of weatherable minerals concern the < 2 µm fraction (Table 1). In the Soil Taxonomy (Soil Survey Staff, 1998; 1999) and the World Reference Base for Soil Resources (ISSS-IRSIC FAO, 1988), only grains ranging from 50 to 200 µm in diameter were considered, because they can be observed on thin sections using optical microscopy.

In the French soil classification (Commission de Pédologie et de Cartographie des Sols, 1967), the possible presence of primary weatherable minerals such as illite was mentioned for the class of Ferralitic soils which corresponds globally to Ferralsols, Acrisols and Lixisols, all of them having reached a similar advanced weathering stage, in the World Reference Base for Soil Resources (ISSS-IRSIC FAO, 1988). The possible presence of 2:1 phyllosilicate as illite or weathered vermiculite in small quantities was later mentioned for the Ferrallitisols of the French Référentiel Pédologique (AFES, 2009). In both systems, neither the size of the grains nor a maximum quantity of weatherable minerals is defined. The only limit mentioned is that the alterable minerals must be present in small quantities (AFES, 2009).

The high number of studies that have shown the presence of weatherable minerals in Brazilian Ferralsols, particularly 2:1 phyllosilicate in the < 2 µm fraction (Table 1), explains why the possible presence of weatherable minerals was mentioned in the Brazilian soil classification (Embrapa, 2018) for both the < 2 µm fraction and the coarser fractions. In their presentation of the Brazilian classification of Latosols, Camargo et al. (1988) specified that latosolic B horizons can "*contain in the fraction < 0.05 mm, as reported to the fine-earth fraction, $<$ 4 percent of any easily weatherable primary minerals, or < 6 percent muscovite*" and that they have "*only rather small proportions of silicate clay minerals less resistant to weathering than kaolinite, with some allowance for aluminum interlayered chlorite*." In the latest issue of the Brazilian soil classification (Embrapa, 2018), the latosolic B horizon was defined in a very similar way as containing not "*more than* 4% *of alterable primary minerals (low resistance to weathering) or* 6% *in the case of muscovite, determined in the sand fraction in relation to the fine earth fraction. The fraction of < 0.05 mm (silt + clay) may contain small quantities of interstratified clay or illite, but not more than traces of clay minerals of the smectite group*.".

Nowadays, soil classifications and other reference systems for naming soils recognize, as does the World Reference Base for Soil Resources (IUSS Working Group WRB, 2022), that in soils such as Ferralsols, "*which result from a long and intense weathering*", "*the clay fraction is dominated by low-activity clays and contains various amounts of resistant minerals such as (hydr-)oxides of Fe, Al, Mn and Ti*". The ferralic horizon is however defined in accordance with 6 diagnostic criteria among which criterion number 4 specifies that "*A ferralic horizon consists of mineral material and has* $>$ 10% *(by grain count) easily weatherable minerals in the 0.05–0.2 mm fraction.*" Thus, without an explanatory scheme being proposed, the main reference systems for naming soils recognize the presence of weatherable minerals in apparent contradiction, at the very least, with the mineralogy and geochemical context of Ferralsols.

3. Characteristics of the Ferralsols where 2:1 phyllosilicates were recorded

3.1. Parent material

Generally, little or no information is available regarding the mineralogy of the parent materials of Ferralsols in which 2:1 phyllosilicates have been found. The analysis of the literature (Table 1) showed that 2:1 phyllosilicates were found in Ferralsols overlying a wide variety of parent materials that may contain micas such as granite (Mafra et al., 2002; Pacheco et al., 2018), gneiss (Cunha et al., 2009), schist (Ferreira et al., 2010), shale (Le Roux, 1974; Khawmee et al., 2013), siltstone (Vidal-Torrado et al., 1999), sandy or clayey metasediments (Reatto et al., 2010; Bruand et al., 2023; 2024), sandstone (Maquère, 2008; Alves et al., 2013), limestone (Jones et al., 1982; Khawmee et al., 2013; Bruand et al., 2022) and poorly consolidated sediments (Ogawa et al., 1981; Arkcoll et al., 1985; Sanz-Scovino et al., 1992; Mujinya et al., 2013). Thus, micas present in these parent materials can be sources of 2:1 phyllosilicates for the overlying Ferralsols.

Although 2:1 phyllosilicates are absent in basalt, their presence was shown in numerous Ferralsols developed on basalt and more widely on alkaline ultramafic rocks in South America (Moura Filho and Buol, 1972; Escobar et al., 1973; Kämpf et al., 1995; Melo et al., 2004; de Oliveira et al., 2004; Soares et al., 2005; Rolin Neto et al., 2009; Inda et al., 2010; Marques et al., 2011; Caner et al., 2014; Oliveira et al., 2020), Africa (Le Roux, 1973; Fey, 1974), Central America (Ryan and Huertas, 2009; Pincus et al., 2017; Ryan et al., 2024) or Asia (Ogawa et al., 1981; He et al., 2008; Darunsontaya et al., 2012; Khawmee et al., 2013; Ndzana et al., 2019; Li et al., 2024). As shown by Caner et al. (2014) in the saprolite of a basalt underlying a Ferralsol developed under a subtropical climate in southern Brazil, 2:1 phyllosilicates may form during the weathering of primary minerals such as celadonite present in basalt vesicles (Korchagin et al., 2019). This would explain the presence of 2:1 phyllosilicates recorded in numerous Ferralsols developed on alkaline ultramafic rocks as mentioned above (Caner et al., 2014) because they are formed through neogenesis processes in the saprolite.

The presence of 2:1 phyllosilicates was also shown in the upper horizons of Ferralsols developed over quartzite and sandstone. The possible presence of 2:1 phyllosilicates in these parent materials remains debated because there was little or no information available about the parent material (Reatto et al., 2000; 2007; 2010; Alves et al., 2013).

3.2. Texture of the horizons

The horizons of the Ferralsols in which 2:1 phyllosilicates were found (Table 1) and for which information about their particle size composition is available had an average silt content of 12% except for three of them for which it was a little higher (Fig. 6). A high proportion of horizons (70%) had even an average silt content $< 10\%$. The coarse and medium texture was recorded for Ferralsols developed on parent material with a high content of sand-sized quartz grains such as granite, sandstone, sandy sediments or metasediments (Maquere, 2008; Mafra et al., 2002; Alves et al., 2013; Pacheco et al., 2018). Finally, the fine and very fine texture was recorded for Ferralsols developed on basalts or more widely alkaline ultramafic parent materials where the amount of sand-sized quartz grains was very low (Moura Flho and Buol, 1972; Escobar et al., 1973; Kampf et al., 1995; de Oliveira et al., 2004; Rolin Neto et al., 2009; de Oliveira et al., 2020). The relatively high silt content recorded for the latter Ferralsols (i.e. $> 10\%$) might correspond to secondary gibbsite and haematite grains as shown by Van Ranst et al. (2019) in Ferrallitic soils developed on volcanic ash deposit in Cameroon or incomplete dispersion (Bartoli et al., 1991).

3.3. Median depth of the horizons

The frequency of horizons in which 2:1 phyllosilicates were found was plotted according to the median depth of the horizon (i.e. the depth of the middle of the horizon considered) (Fig. 7). Among the 235 horizons considered, half correspond to horizons whose median depth is less than 50 cm (Fig. 8). Almost all of the other half of the horizons have an average depth between 50 and 200 cm (84 horizons). The majority of the 38 horizons with a median depth between 200 and 1000 cm come from the study published by Chiapini et al. (2023). Their study concerned very deep autochthonous Brazilian Ferralsols of the Paraná Igneous Province. Thus, we cannot infer from the distribution shown in Fig. 7 that the 2:1 phyllosilicates are essentially present in the first top 50 cm of the Ferralsols. This is clearly a sampling bias which highlights the interest in looking for these 2:1 phyllosilicates across the entire thickness of the Ferralsol, from the surface horizon to the bottom of the Ferralsol as performed by Chiapini et al. (2023) for four of the ten-meter-deep Ferralsols they studied, or even down to the upper part of the saprolite, which has only been done a few times so far (Vidal-Torrado and Lepsch, 1999; Paisani et al., 2013; Caner et al., 2014, Mancini et al., 2021; Chiapini et al., 2023).

4. Size, chemical composition and mineralogy of the 2:1 phyllosilicate particles

The characteristics of 2:1 phyllosilicates present in highly weathered soils dominated by 1:1 clay minerals and iron and aluminum oxyhydroxides that include Acrisols, Lixisol, Nitisols, Ferralsols and Durisols (IUSS Working Group WRB, 2022) has been discussed since long (e.g. Jackson, 1962; Bain, 1977; Herbillon, 1980; Juo, 1980; Ross et al., 1982; Barnhisel and Bertsch, 1989) up to recent years (Ndayiragije and Delvaux, 2003; Georgiadis et al., 2020; Van Ranst et al., 2020).

Regarding Ferralsols only, the terminology used to name these 2:1 phyllosilicates has historically varied (Table 1), reflecting the debate concerning their geochemical and crystallographic characteristics, origin, and stability in relation to geochemical processes during weathering and pedogenesis (Barnhisel and Bertsch, 1989; Georgiadis et al., 2020). The analysis of the literature showed that since the early studies, 2:1 phyllosilicates were identified using XRD always in the < 2 μm fraction when present, often in the 2–50 μm fraction, and sometimes in the 50–2000 μm fraction (Table 1). Detailed analysis of the < 2 μm fraction of the Bw horizon of Brazilian Latosol also showed early on that they were mainly present in the 0.2–2 μm fraction, the so-called coarse clay fraction, and then identified as partly mica and partly vermiculite (Escobar et al., 1973). Analyzing the main horizons of two Oxisols in a Brazilian Oxisol-Ultisol toposequence, Lepsh and Buol (1974) showed that 2:1 phyllosilicates were present as much in the 0.2–2 μm fraction as in the < 0.2 μm fraction called fine clay. They were identified at that time as being mainly chlorite/vermiculite intergrade clay minerals with a small amount of mica and vermiculite (Table 1). Much more recently, Bertolazi et al. (2017) used XRD to study the bulk < 2 μm fraction, and the 0.1–2 μm, 0.05–0.1 μm, and < 0.05 μm fractions of a Brazilian Rhodic Hapludox (Fig. 2). They showed that most 2:1 phyllosilicates, which were identified with the peak at 1.47 nm in the < 2 μm fraction, were essentially present in the 0.1–2 μm fraction. According to Bertolazi et al. (2017), the absence of swelling following solvation with ethylene glycol indicated that the peak at 1.47 nm could be assigned to vermiculite or hydroxy-Al-interlayered minerals (HIMs).

In recent years, Darunsontaya et al. (2010 and 2012) studied Oxisols from Thailand and published pictures of K-bearing particles of a few micrometers in size recorded by using transmission electron microscopy (Fig. 3). They showed also that the K_2O content ranged from 2.8 to 5.7%. These particles were interpreted as being illite, HIV or smectite shown by conventional and synchrotron XRD. They were observed even in Oxisols where conventional XRD did not show the presence of 2:1 phyllosilicates (Darunsontaya et al., 2012). Backscattered electron scanning images (BESI) of polished cross sections of undisturbed samples impregnated with a polyester resin (Bruand et al., 1996), were used to visualize images of 2:1 phyllosilicates within the undisturbed groundmass of B horizons originating from Ferralsols located in the Brazilian Central plateau (Bruand and Reatto, 2022; Bruand et al., 2022; 2023; 2024). Depending on the Ferralsols studied, the elementary particles of 2:1 phyllosilicates observed ranged from particles in the fine sand fraction down to the clay fraction (Bruand and Reatto, 2022; Bruand et al., 2022; 2023; 2024) (Fig. 4). The sand and silt sized elementary particles of 2:1 phyllosilicates were shown to have the average structural formula of weathered muscovite, based on the chemical compositions recorded using EDS chemical analyses (Table 2). The chemical analyses according to the size of the particles showed that the chemical composition for the largest elementary particles corresponded to weakly weathered muscovite, and to HIV for the smallest ones (Bruand and Reatto, 2022) (Fig. 5). However, it cannot be ruled out that part of the surrounding groundmass was also taken into account in the volume analyzed for the coarse clay-sized particles selected. This remains a limitation for the interpretation of the chemical analyses performed. A coupled XRD analysis of the coarse and fine clay fraction such as that performed by Bertolazi et al. (2017) would have allowed more precise conclusions regarding the mineralogy of the coarse- and fine-sized clay particles observed on the BESI.

Beyond these studies showing the very frequent presence of 2:1 phyllosilicates in Ferralsols, other studies have clarified the nature of these minerals when Ferralsols developed over alkaline mafic rocks that did not contain any muscovite particle. Caner et al. (2014) studied the weathering of basalt and dacite and soil clay formation in Brazilian Ferralsols. By combining X-ray diffraction, chemical extraction and Fourier transform infrared (FTIR) spectroscopy, they showed that hydroxy-Al interlayered minerals present in the surface horizons originated from the aluminization of smectite (i.e. hydroxy-Al interlayered smectite, HIS) present in the saprolite under the acidic conditions prevailing in surface horizons rich in organic matter (Fig. 1). These smectites resulted originally from the weathering of primary minerals within the saprolite. We can thus hypothesize that the hydroxy-Al interlayered smectite identified early by Kampf et al. (1995) in Latosols developed on basalt, and more widely on alkaline mafic rocks, originated from smectite that formed through neogenesis processes in the saprolite of the

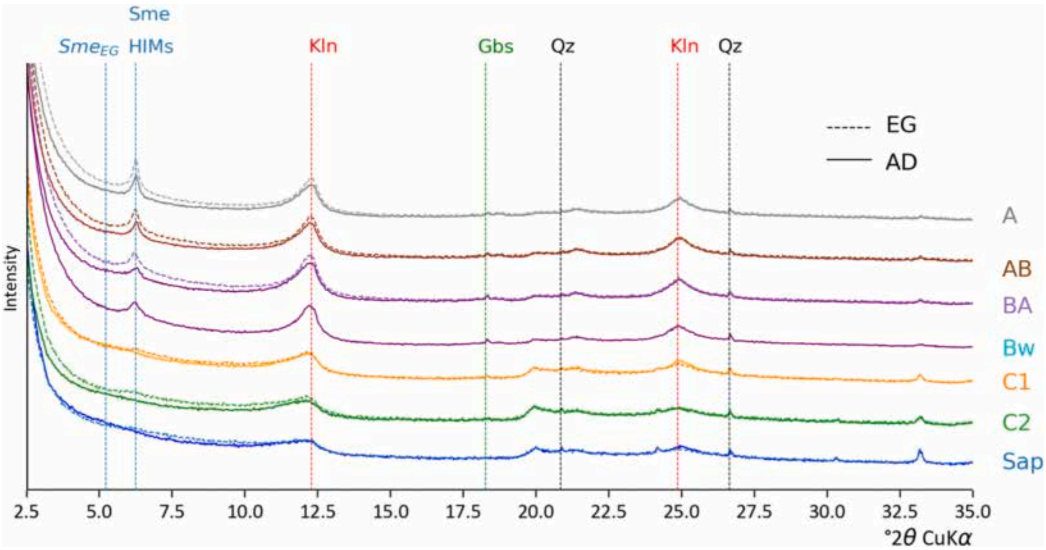


Fig. 1. X-ray diffraction patterns of the < 2 μm fraction extracted from the horizons of a Brazilian Ferralsol developed on basalt (modified after Caner et al., 2014). The solid black line is air-dried treatment (AD), the solid grey line is after ethylene glycol treatment (EG). Kln: kaolinite, SAD and SEG: smectite AD and EG; HIMs: hydroxy-aluminum-interlayered-minerals; Gt: gibbsite; Qz: quartz.

parent material.

Finally, some studies have shown that a high proportion of the 2:1 phyllosilicates present were interstratified minerals resulting from the weathering of the 2:1 phyllosilicates present in the parent material with mica/HIV (Cunha et al., 2019), illite/vermiculite (Mafra et al., 2002; Ndzana et al., 2019), illite/smectite (Poss et al., 1991), or of the vermiculite/chlorite (Lepsch and Buol, 1974; Møberg and Esu, 1991), although in the latter case, it was more likely vermiculite/HIV. In addition to X-ray diffraction studies, observations made by Bruand and Reatto (2022) and Bruand et al. (2024) using backscattered electron scanning imaging clearly demonstrated the existence of distinct types of interplanar paces within 2:1 silt-sized phyllosilicates in ferralic horizons of Brazilian Ferralsols. However, the presence of 2:1/1:1 interstratified phyllosilicates in Ferralsols, as reported in other intertropical soils (Van Ranst et al., 2020; Delvaux et al., 1990), remains scarce with only a few studies showing their presence (Ryan and Huertas, 2009; Pincus et al., 2017; Testoni et al., 2017; Ryan et al., 2024).

5. Origin of the 2:1 phyllosilicates present in Ferralsols

5.1. Neoformed minerals from the soil solution

While many studies have focused on the desilication and resilication processes of clay minerals in saprolites and soils (Herbillon et al., 1977; Herbillon, 1980; Karathanasis et al., 1983; Barnhisel and Bertsch, 1989; Lucas et al., 1993; Buol and Eswaran, 1999; Karathanasis, 2002; Cornelis and Delvaux, 2016; Tombeur et al., 2020), few have proposed that 2:1 phyllosilicates can neoform from the soil solution in Ferralsols (Karathanasis et al., 1983; Barnhisel and Bertsch, 1989; Buol and Eswaran, 1999; Karathanasis, 2002). Given the geochemical context in Ferralsols, where desilication of primary minerals and of their weathering products occurs when Si is still retained in their mineral lattice, it is difficult to hypothesize that 2:1 phyllosilicates could form from the soil solution, particularly in the ferralic horizon. However, Inda et al. (2010) showed that the chemical composition of the soil solution extracted from a subtropical Brazilian Oxisol developed on a basalt revealed that Al and Si activities in the soil solution were indeed thermodynamically in equilibrium with 2:1 phyllosilicates of which the interlayer space was partially occupied by hydroxy-Al. Resilication processes were also envisaged by Pacheco et al. (2018) in topographical positions such as plateau edges or on slopes as observed according to the drainage regime with the possible neoformation of 2:1 phyllosilicates. Finally, it is also worth mentioning that in environments favoring desilication, phytochemical silicon recycling can be a source of Si in resilication processes, or maintain a level of aqueous Si that can favor the stability of clay minerals, as shown in tropical soils (Lucas et al., 1993; Cornelis and Delvaux, 2016; Tombeur et al., 2020; Zhang et al., 2026).

5.2. Minerals inherited from the parent material

The 2:1 phyllosilicates evidenced in many A and B horizons of Ferralsols were commonly considered to be inherited from the parental material. They present varying degrees of transformation depending on their initial characteristics and the intensity of desilication and aluminization processes (hydroxy-Al intercalation in the interlayer space). Therefore, when Ferralsols develop on granite, gneiss or schist (Lelong and Millot, 1966; Mafra et al., 2002; Cunha et al., 2004; Ferreira et al., 2010; Pacheco et al., 2018), the 2:1 phyllosilicates found in the A or B horizon exhibit analytical characteristics consistent with hydroxy-Al interlayered 2:1 phyllosilicates, specifically HIV and may result from mica weathering. Ker (1995) found 2:1 phyllosilicates showing the characteristics of HIV in Ferralsols developed on limestone and amphibolite and assumed that they resulted from the transformation of mica or chlorite present in the parent material. Britto Galvão and Schulze (1996) found mica occurring mainly in the 2–5 μm fraction throughout the 2 m profile of the Ferralsol developed on limestone and siltstone that they studied. The presence of mica was interpreted by the authors to indicated inheritance from the parent material and the traces of hydroxy-Al-interlayered-vermiculite also present throughout the 2 m profile as resulting from mica weathering. These 2:1 phyllosilicates were qualified as "*recalcitrant minerals*" by Moterle et al. (2019), thus highlighting the inherited character of these minerals when they are present both in Ferralsols and in their parent material.

When Ferralsols were developed on basalt or more widely on alkaline ultramafic rocks (Escobar et al., 1973; Fey, 1974; Melo et al., 2004; Caner et al., 2014; de Oliveira et al., 2020), the 2:1 phyllosilicates evidenced in the A or B horizon show analytical characteristics of hydroxy-Al interlayered 2:1 phyllosilicate. They can be considered in the Ferralsols studied as resulting from the interlayering by hydroxy-Al of smectites originating from weathering processes within the saprolite of the parent material (Caner et al., 2014).

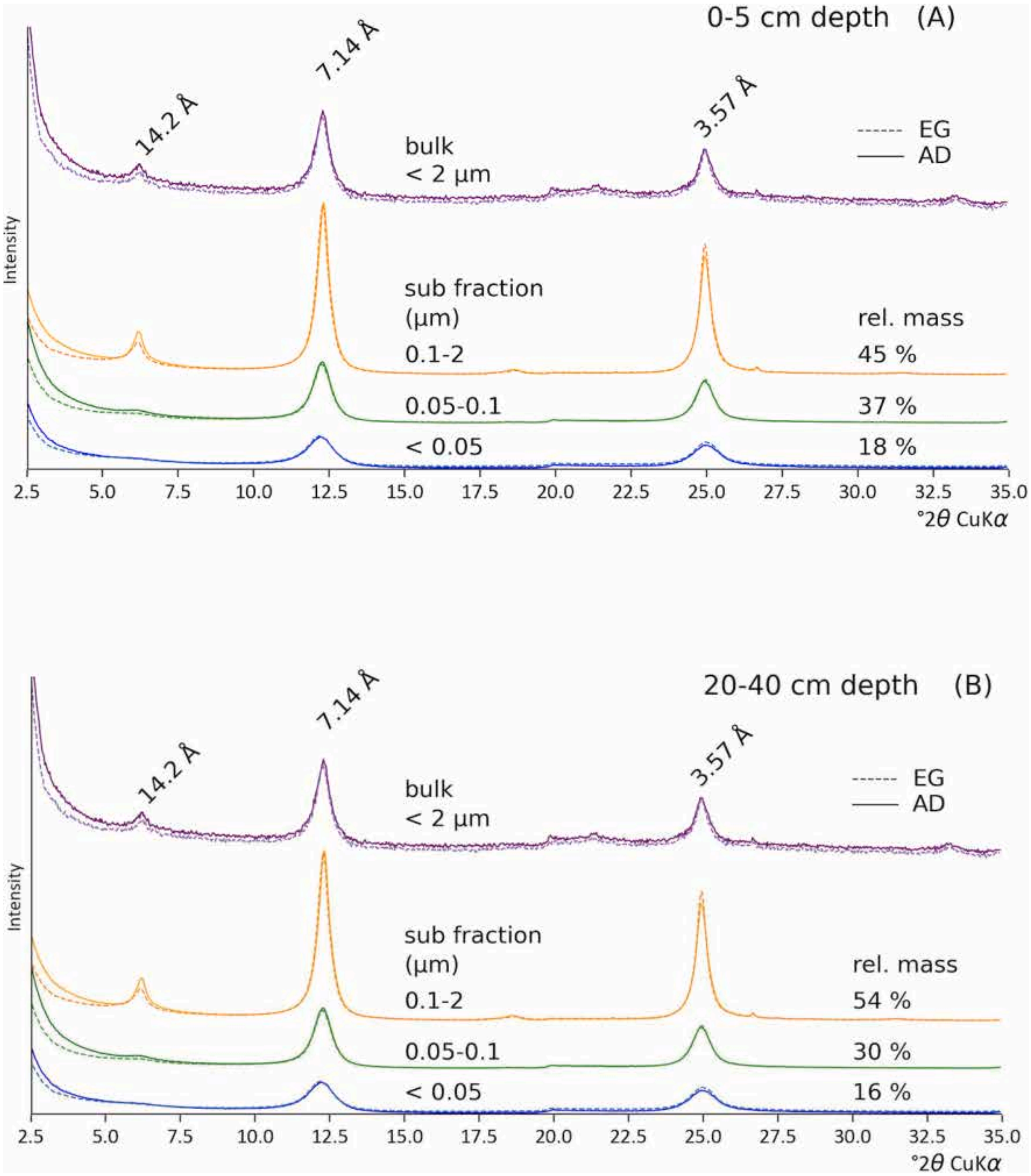


Fig. 2. X-ray diffraction patterns recorded for the bulk clay fraction (< 2 µm), and for the clay subfractions 0.1–2 µm, 0.05–0.1 µm and < 0.05 µm at 0–5 cm (A) and 20–40 cm depth in Brazilian Oxisol (modified after Bertolazi et al., 2017). Comparison of Ca-saturated air-dried sample (AD, black solid line) and Ca-saturated ethylene glycol (EG, grey solid line). The relative mass (rel. mass) of each subfraction was normalized to 100%.

Finally, it should also be noted that, from a thermodynamic perspective, the stability of these 2:1 phyllosilicates may be comparable to that of 2:1:1 phyllosilicates due to the partial aluminization of their interlayer space (Robert and Veneau, 1974; Tardy and Garrels, 1974; Karathanasis et al., 1983; Karathanasis, 2002). Locally, they exhibit a mineralogical structure similar to that observed for 1:1 phyllosilicates, thereby mimicking monosiallitization, and can therefore be considered to possess a‘ thermodynamic stability close to that of the latter (Karathanasis, 2002; Ndayiragiya and Delvaux, 2003). Thus, once their interlayer space is partially aluminized, these 2:1 phyllosilicates may effectively behave as "recalcitrant minerals" with respect to weathering (Moterle et al., 2019), persisting in ferralitic horizons where gibbsite and Fe oxyhydroxides dominate (Karathanasis, 2002; Ndayiragije and Delvaux, 2003).

5.3. Allochthonous minerals brought by atmospheric transport

Although no studies, to our knowledge, have demonstrated long-range atmospheric inputs of silt and clay-sized particles containing potassium-bearing 2:1 phyllosilicates for Ferralsols, the possibility of such inputs occurring, as with other soil types in intertropical regions, cannot be ruled out (Dymond et al., 1974; Prospero et al., 1981; Kurtz et al., 2001; Nakao et al., 2021). It should be noted that although atmospheric inputs cannot explain the presence of 2:1 phyllosilicates in all the Ferralsol profile where they have been identified – Ferralsols frequently having thicknesses exceeding several meters (Fey, 1974; Antonello, 1988; Maquere, 2008; Rolim Neto et al., 2009; Retto et al., 2010; Mujinya et al., 2013; Paisani et al., 2013; Mancini et al., 2021) – their potential contribution to the 2:1 phyllosilicate stock in the surface horizons cannot be excluded as shown for soils other than Ferralsols

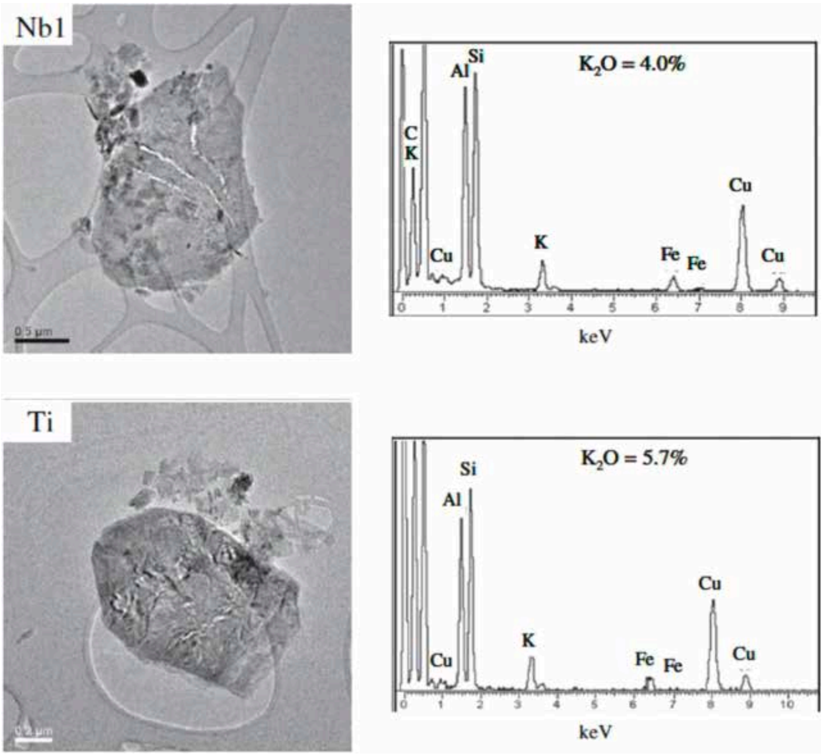


Fig. 3. Transmission electron micrographs, X-ray spectra and K2O content of illite particles from the clay fraction of two Thai upland Oxisols (modified after Darunsontaya et al., 2012).

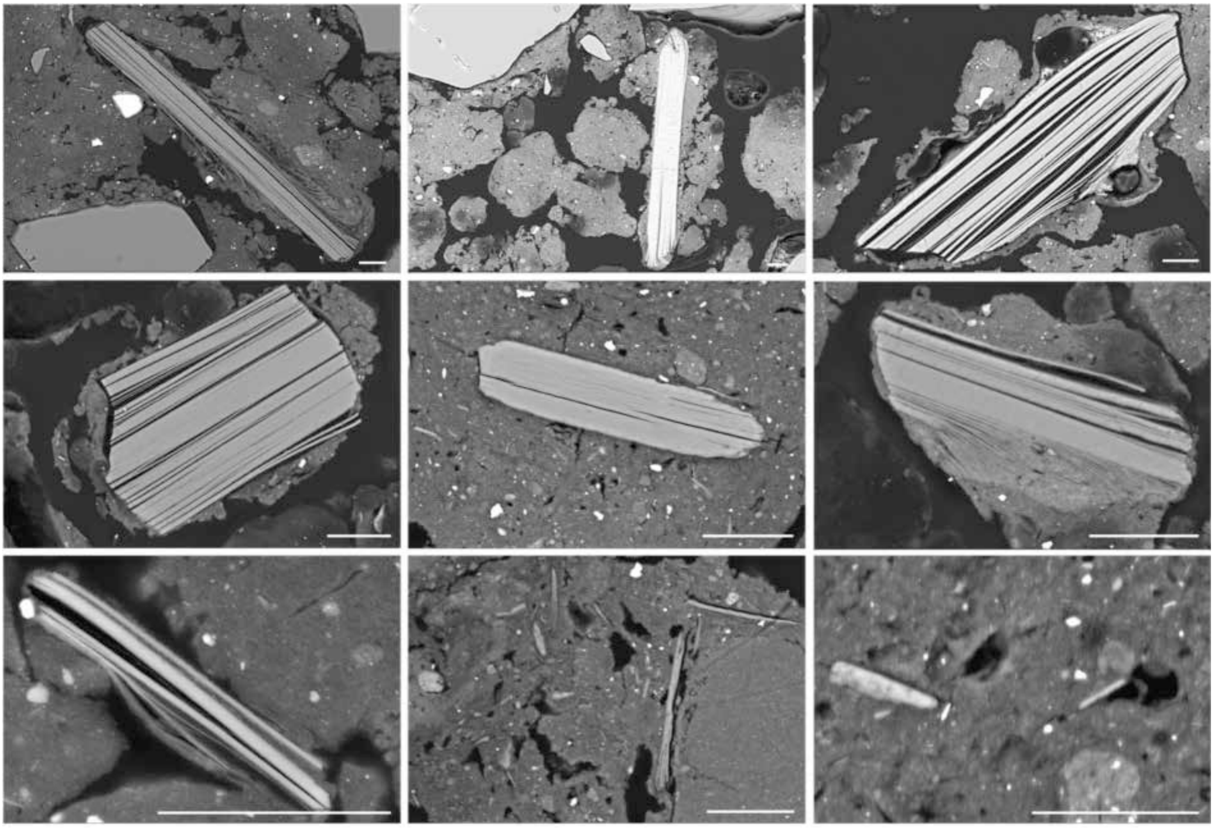


Fig. 4. Sand and silt sized particles of 2:1 phyllosilicates observed on backscattered electron scanning images (BESI) of polished sections of samples collected in Ferralic horizons studied by Reatto et al. (2007, 2008 and 2009) and Bruand et al. (2023) (Bruand, unpublished). Similar particles were shown to range from weakly weathered muscovite (the largest particles) to HIV (the smallest particles) (Bruand et al., 2022). Bar length: 20 µm.

Table 2

Averaged structural formulae computed for silt-size particles of 2:1 phyllosilicates observed in 10 ferralic B horizon of Ferralsols located in the Cerrado region (Brazil) (modified after Bruand et al., 2024). X, number of octahedral cavities occupied per half-unit-cell (X = c + d + e + f); Y, sum of the charges of the cations in the interlayer space (Y = g + (2 × h) + i). Structural formulae for a theoretical muscovite (Velde and Meunier, 2008) and a muscovite of a granite (Aurousseau et al., 1983) are also given.

Structural formulae		$\left[Si_a^{4+}Al_b^{3+}\right]O_{10}^{2-}\left[Al_c^{3+}Fe_d^{3+}Mg_e^{2+}Ti_f^{4+}\right](OH)_2^{-}K_g^{+}Ca_h^{2+}Na_i^{+}$										
		a	b	c	D	e	f	g	h	i	X	Y
Particles of 2:1 phyllosilicates	Mean	3.05	0.95	1.75	0.18	0.09	0.03	0.75	0.01	0.10	2.06	0.87
	s.d.	0.06	0.06	0.08	0.07	0.04	0.01	0.10	0.01	0.09	0.04	0.09
Theoretical muscovite		3.00	1.00	2.00	0.00	0.00	0.00	1.00	0.00	0.00	2.00	1.00
Muscovite in a granite		3.16	0.84	1.66	0.07	0.28	0.05	0.95	0.00	0.00	2.01	0.95

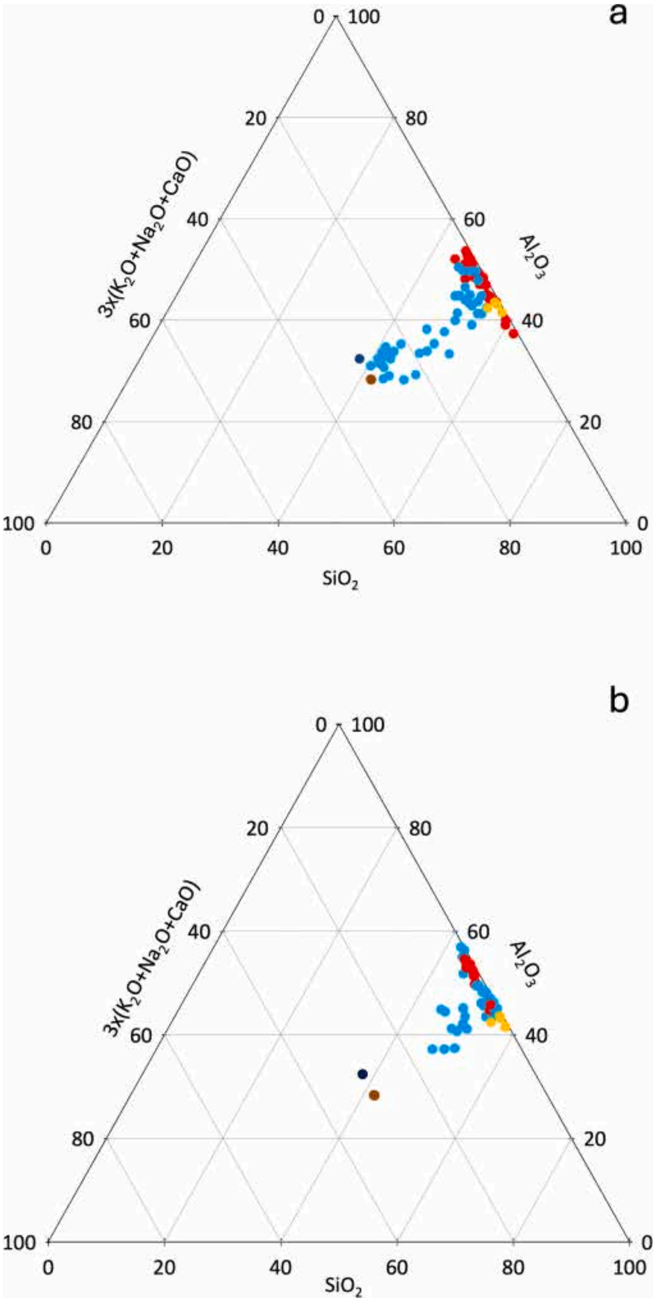


Fig. 5. Respective content in Al_2O_3, SiO_2 and $K_2O + Na_2O + CaO$ in sand-coarse silt-size particles of 2:1 phyllosilicates (light blue dots) and surrounding groundmass (red dots) of the Bw horizon of a Brazilian Ferralsol (a), and in small silt-size and coarse clay-size particles of 2:1 phyllosilicates (light blue dots) and surrounding groundmass (red dots) of the same Bw horizon (b), in a theoretical muscovite (deep blue dot), in muscovite particles (brown dots) and in weathered muscovite particles (yellow dots) (modified after Bruand and Reatto, 2022).

(Tiessen et al., 1991; Lyngsie et al., 2011; Kitagawa et al., 2024).

5.4. *Relict minerals carried from the weathered parent material by social insects*

If we retain the hypothesis that the 2:1 phyllosilicates have to be considered as relict materials originating from the parent material or from the saprolite which results from its weathering, the question remains of their presence in the A horizons, given that Ferralsols result from a very long geochemical evolution and that they can be up to more than ten meters thick (Ortigao et al., 1996). Rodrigues-Netto (1996) found 2:1 phyllosilicates with the characteristics of HIV in Ferralsols developed on several parent materials and concluded that their presence was independent of the relative weathering intensity. Thus, even assuming that these minerals originate from the parent rock, they cannot be considered as simple relict minerals, present only because of their resistance to physico-chemical weathering processes for hundreds of thousands of years, as the mineral matrix surrounding them is massively composed of minerals reflecting intense weathering. It is therefore necessary to consider an origin other than a direct inheritance from the parental material without the intervention of another process.

Recent results indicate that this presence across the entire thickness of Ferralsol results from the activity of social insects, mainly termites (Bruand and Reatto, 2022; Bruand et al., 2022 and 2023) but also ants (Nascimeno et al., 2024; Chiapini et al., 2025). The presence at shallow depth of particles the size of silts or fine sands, presenting the weathering patterns and chemical compositions of muscovite as shown in several Ferralsols, is difficult to explain without involving bioturbation by social insects (Fig. 4). Likewise, the presence at shallow depth of saprolite material fragments in the gibbsitic and kaolinitic groundmass of ferralic horizons is an additional argument in favor of the role of social insects to explain why very small weathered particles of phyllosilicate minerals can be present at shallow depth in Ferralsols (Figs. 8 and 9).

A greater amount of clay minerals has been recorded by several authors in termite constructions (epigeous mounds and sheeting and belowground tunnel and chamber walls). The role of these minerals is to make the constructions more stable and allow them to better regulate temperature and humidity (Jouquet et al., 2016a, b). Among these clay minerals, 2:1 phyllosilicates originating from the bottom of the soil were recorded in epigeous termite mounds while they were considered absent from the A and B horizons of the surrounding Ferralsols (Jouquet et al., 2020). Such very deep sampling can be explained by both the higher content of clay minerals at the base of the Ferralsols in the saprolite of the parent material and the fact that the clay minerals present there have more appropriate properties than in the A and B horizons of the Ferralsols where only low-activity clays such as kaolinite are present. Among the exchangeable cations potentially still present in the interlayer space of 2:1 phyllosilicates in the saprolite, Na^+ is particularly sought after, as this chemical element is most often absent from the vegetation consumed by termites while it plays an important role in the regulation of termites' physiological processes (Jouquet and Bruand, 2023). Such a hypothesis is consistent with the increase in termite activity following the addition of Na^+ in the soil and litter as was observed in the Peruvian Amazon forest (Kaspari et al., 2009), in Ecuador (Kaspari

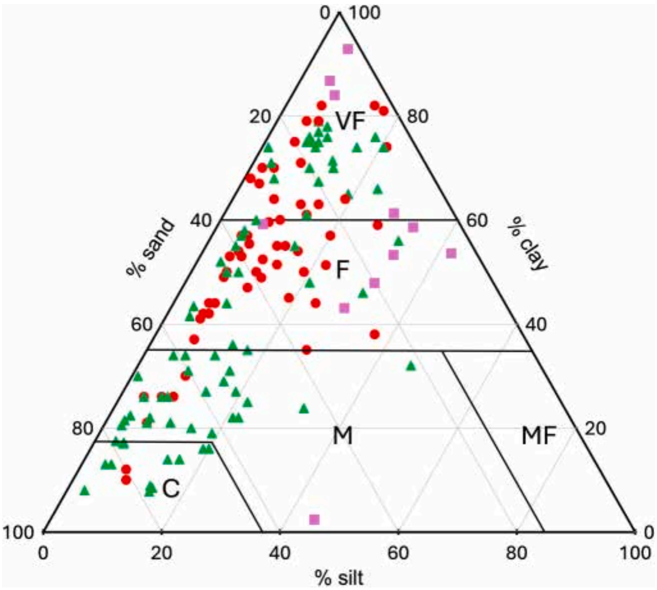


Fig. 6. Particle size distribution and corresponding texture (FAO, 1990) of the horizons of Ferralsols (IUSS Working Group WRB, 2022) and equivalent soils according to other soil classifications in which 2:1 phyllosilicates were found (red circles: Ferralsols of Africa; green triangles: Ferralsols of South America; purple squares: Ferralsols of Asia).

et al., 2014) and in the Panama rainforest (Clay et al., 2014). It can therefore be suggested that the presence of 2:1 phyllosilicates in Ferralsols is the consequence of this clay mining activity in the saprolite of the parent material, an activity motivated by the collection of clay material for its physical properties but also as a source of Na^+ which is missing in the food ration of termites.

Thus, for reasons still poorly understood, termites, and possibly ants, activity appears to transport to soil surface materials from saprolite and deep horizons of the Ferralsols, still rich in 2:1 phyllosilicates undergoing weathering or formed by neogenesis depending on the nature of the parent material. It is suggested that these materials are incorporated into termite or ant mounds and, incidentally, seeded in the soil horizons during transport, influencing the mineralogical composition of the Ferralsol profile. If this interpretation is correct, they are indeed allochthonous relict minerals following their transport by termites or ants, and continue to weather in the horizons where they are observed today, depending on the surrounding geochemical context. This interpretation is consistent with the role of termites and ants that has been shown in the formation of Ferralsols, particularly their micro-granular structure (Schaefer, 2001, Jouquet et al., 2016c, Nascimento et al., 2024; Bruand, 2025).

It is worth noting also that this interpretation does not contradict the idea that these 2:1 phyllosilicates may behave as recalcitrant minerals with respect to weathering once they have been redistributed by the burrowing activity of social insects into ferralitic horizons dominated by gibbsite and Fe oxyhydroxides, as discussed above (Karathanasis, 2002; Ndayiragije and Delvaux, 2003).

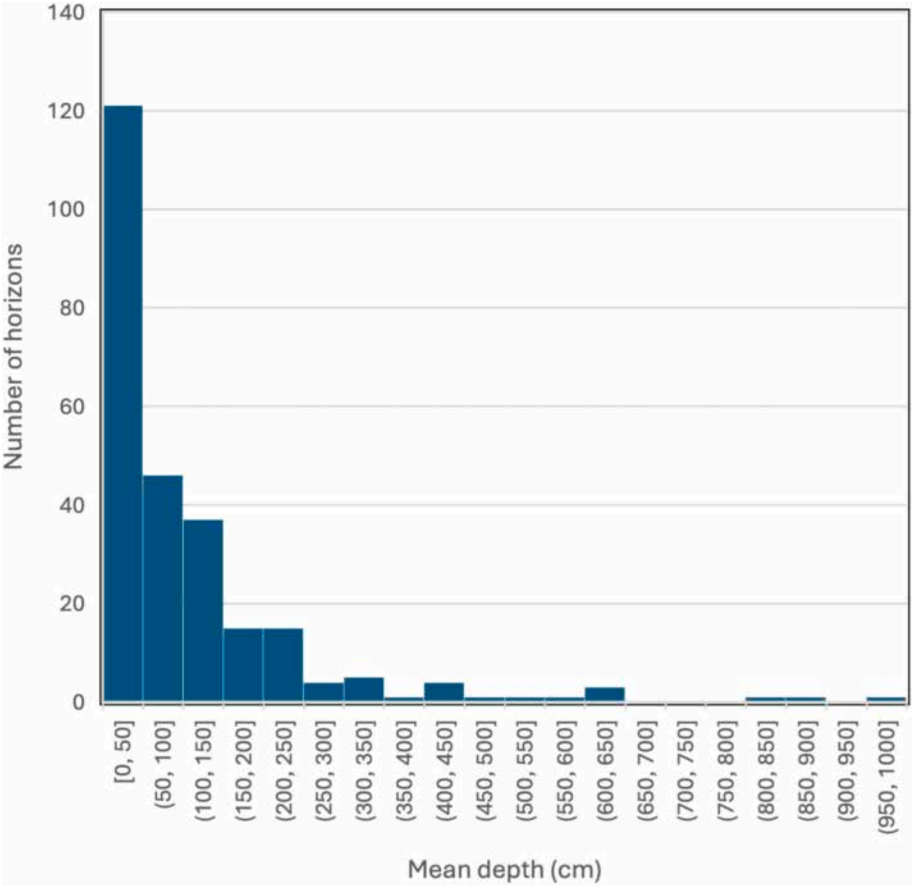


Fig. 7. Frequency of horizons of Ferralsols (IUSS Working Group WRB, 2022) and equivalent soils according to other soil classifications in which 2:1 phyllosilicates were found according to median depth of the horizon (i.e. depth of the middle of the horizon).

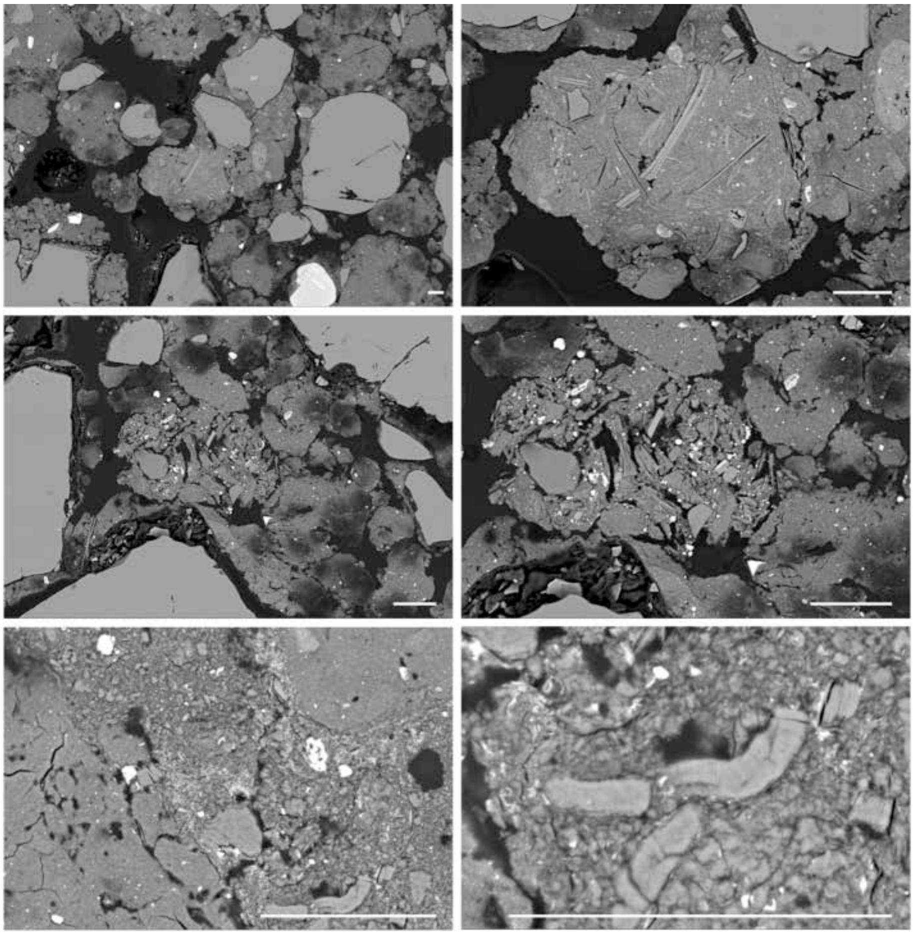


Fig. 8. Allochthonous material originating from saprolite and observed on backscattered electron scanning images (BESI) of polished sections of samples originating from ferralic horizons (Bruand, unpublished). Submillimetric granular aggregates showing a much higher content in 2:1 phyllosilicates (P) than in the surrounding submillimetric granular aggregates: a, b, c and d (Ferralic horizon of the Ferralsol L1 studied by Reatto et al. (2007; 2008; 2009), and the presence of large particles of kaolinite (K): e and f (Ferralic horizon of the Ferralsol L6 studied by Reatto et al. (2007; 2008; 2009). Bar length: 50 µm.

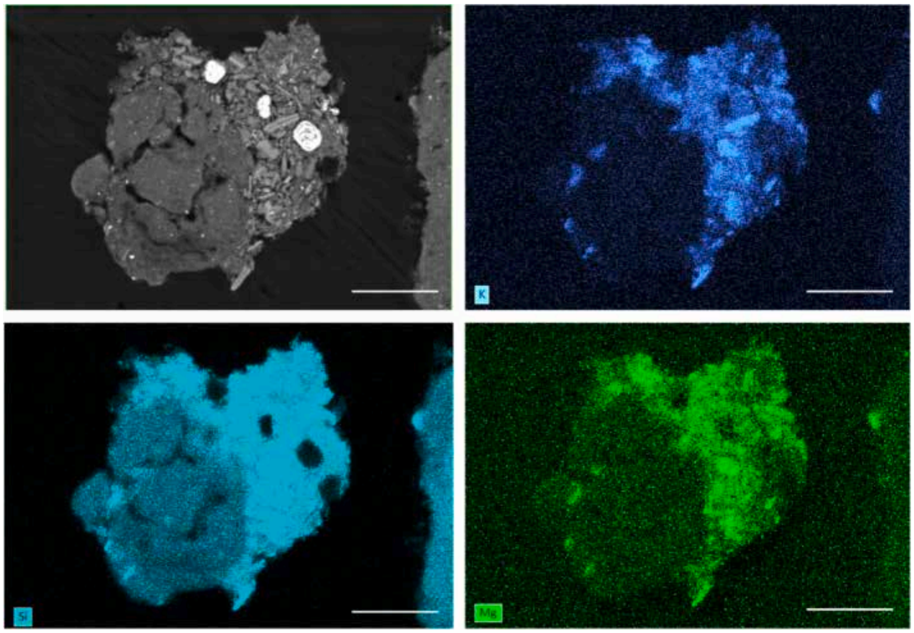


Fig. 9. Allochthonous material originating from saprolite and attached to several submillimetric granular aggregates (Bruand, unpublished). Observation made in the ferralic horizon (100–160 cm) of the Ferralsol L1 studied by Reatto et al. (2007; 2008; 2009). Backscattered electron scanning image (BESI) (a) and maps of the K, Si and Mg concentrations (b, c and d, respectively) recorded using energy dispersive spectrometry (EDS). Bar length: 20 µm.

6. Consequences for Ferralsol properties

6.1. Contribution of 2:1 phyllosilicates to the potassium dynamics

The 2:1 phyllosilicates present in Ferralsols can contribute to the total K stock if they have potassium in the interlayer space. This contribution to the K stock and their participation in potassium dynamics, such as the K fertility of these soils can be questioned (Manning, 2010). The mineral reserves of K are known to be particularly low in most highly weathered tropical soils (300 – 2000 mg kg^{-1}) such as Ferralsols compared to most temperate zone soils (Zörb et al., 2014). Quantification of the K reserve related to the presence of 2:1 phyllosilicates in Ferralsols was performed early by Arkcoll et al. (1985). They studied Oxisols under native vegetation from the Manaus region of Brazil and showed that the total K content ranged from 100 to 300 mg kg^{-1}, depending on the horizon and soil studied. The highest total K content corresponded to the horizon with the highest clay content. They also showed that, depending on both the soil and horizon studied, only 15 to 35% of the total K content corresponded to exchangeable K. Alves et al. (2013) studied the mineral reserve of K in a Ferralsol under a vegetation of *Pinus* species where 2:1 phyllosilicates identified as mica were recorded in the sand, silt and clay fractions and found similar small amounts of total K. The total K content was estimated to range from about 100 to 200 mg kg^{-1} in the A and B horizons studied and only a few percent of that total K were characterized as exchangeable K, the highest values being recorded for the A horizons. The total K content was 510 mg kg^{-1} in the B horizon of a Togolese Ferralsol studied by Poss et al. (1991) under native vegetation and about 5 to 10% of that total K content was exchangeable K, depending on the wetting–drying cycles applied to the soil.

Martins et al. (2004) studied the K mineral reserve in representative soils of Campos Gerais in Brazil and found a much higher total K content. In two of the three latosols studied, they showed the presence of 2:1 phyllosilicates identified as mica and chlorite in the silt and clay fractions and the amount of total K present in these minerals was estimated at around 4000 mg kg^{-1}. Steiner and Lana (2018) measured the total K and exchangeable K content in the A horizon of Brazilian Ferralsols developed under native vegetation on a range of parent material (basalt, shale and sandstone). They likewise found a much higher total K content than that recorded by Arkcoll et al. (1985) and Alves et al. (2013) with a total K content ranging from 1000 to 8562mg kg^{-1}, the proportion of the latter appearing as exchangeable K ranging from 1% to 12%. A relatively high total K content was reported by Sanz-Scovino et al. (1992) for the B horizons of Colombian Oxisols with a content between 800 and 1370 mg kg^{-1} whereas the exchangeable K was low in the soils studied.

Total K content was measured in a Brazilian Oxisol developed under native forest on a basalt where 2:1 phyllosilicates were present in low amounts with 630 mg kg^{-1} of total K content in the whole topsoil (Firmano et al., 2020). Most K content was present in the silt fraction with 900 mg kg^{-1} of total K content and secondarily in the clay fraction with 520 mg kg^{-1} (Firmano et al., 2020). The proportion of exchangeable K was around 15% and varied slightly depending on the method used to quantify it. Bruand et al. (2024) studied the consequences of the presence of 2:1 phyllosilicates on the total K and exchangeable K in a large range of B horizons collected between 1 and 2 m depth in Ferralsols of the Brazilian Cerrado. They showed that the amount of total K in these horizons varied from 300 to 6700 mg kg^{-1} depending on the number and particle size of 2:1 phyllosilicates shown on backscattered electron scanning images. The proportion of exchangeable K in these B horizons ranged from 2 to 10% of the total K content.

Finally, Moterle et al. (2019) studied how the clay mineralogy affected the K dynamics in response to K fertilization during successive cropping. They showed that the 2:1 phyllosilicates identified as vermiculite and hydroxy-Al-aluminum vermiculite, even in very small quantities, control soil K reserves and K availability for plants.

6.2. Contribution to K supply for cultivated plants

As mentioned above, most Ferralsols and corresponding soils in other soil classifications than that established by the IUSS Working Group WRB (2022) were early identified as having an exchangeable K content of less than 0.15 $cmol_{+}$ kg^{-1} in the top horizon. This must be considered as a critical level that will induce a decrease in yield for many crops (Göedert and Lobato, 1988). Whereas the exchangeable K content is higher than that critical level in the A horizon under native vegetation, it decreases rapidly once the vegetation has been cleared and the soil used to grow crops (Poss et al., 1991). The question arises of a possible contribution of K coming from the weathering of the 2:1 phyllosilicates and of the duration of this contribution to K fertilization.

In Togolese Ferralsols, after 15 years of cultivation without any fertilizer application, the exchangeable K in the 0–30 cm horizon decreased from 0.24 to 0.04 $cmol_{(+)}$ kg^{-1} and in the 80–100 cm horizon from 0.06 to 0.03 $cmol_{(+)}$ kg^{-1} (Poss et al., 1991). These authors showed that for the soils studied, the quantity of K released by weathering of the 2:1 phyllosilicates present was estimated at 100–50 kg ha^{-1} $year^{-1}$ of K, which corresponded roughly to an application of K fertilizer for a year. However, the kinetics of K release appeared to be too slow to meet the needs of most cultivated plants. Furthermore, it is probable that in the medium term, the quantity of K that can be mobilized to provide exchangeable K from minerals will decrease over time as the K becomes less and less easily mobilizable over the years (Poss et al., 1991). Silva et al. (2000) studied the forms of K present in Brazilian Latosols and how they affect the growth of two native forest species and of corn crop. They showed that total K content ranged from 6472 to 9187 mg kg^{-1} and from 4242 to 7389 mg kg^{-1}, in the 0–20 cm and 20–60 cm horizons respectively. The proportion of exchangeable K ranged from 10 to 24% in these horizons. Results showed that the capacity of potassium reserves from minerals to meet the needs of plants in the short, medium and long term clearly varies depending on the plant species.

More recently, Darunsontaya et al. (2010; 2012) studied the availability of K to plants as related to the mineralogy of Thai upland Oxisols which contained small amounts of K-bearing 2:1 phyllosilicates. Greenhouse K-depletion experiments by Guinea grass uptake were conducted and showed that plants survived for six harvests for the clay Oxisols studied (Darunsontaya et al., 2012). However, a detailed analysis of the K availability according to the greenhouse experiments showed that K exhaustion of soils would occur in the field after a few years, requiring the application of K fertilizer to balance K export by crops, confirming the earlier results of Poss et al. (1991). In a recent study, Moterle et al. (2019) performed greenhouse experiments on a Brazilian Ferralsol containing 2:1 phyllosilicates identified as 2:1 hydroxy-Al interlayer phyllosilicates during eight different crop cycles. They showed that no K application resulted in limited crop yields compared to those recorded with K application. They also showed that no K application diminished in eight years the proportion of 2:1 phyllosilicates in the soil in relation to the kaolinite content.

Other studies focused on the state of the K reserves in Ferralsols after years of cultivation without K supply. Thus, Steiner and Lana (2018) studied the contribution of non-exchangeable K to plant nutrition in Oxisols from southern Brazil developed on basalt, shale and sandstone and where 2:1 phyllosilicates were present. Based on greenhouse experiments after six successive croppings without or with K fertilization, they showed that when the soils were not fertilized with K, the successive plant cultivation resulted in a continuous process of depletion of non-exchangeable K and exchangeable pools. The non-exchangeable K contribution to K nutrition of plants without and with K fertilizer ranged from 50 to 73% and from 4 to 8%, respectively. Firmano et al. (2020) studied the K reserves in southern Brazilian Oxisols cultivated for 32 years without and with K fertilization. In the plots without K fertilization, the plants manifested K deficiency and the 2:1 phyllosilicates showed a smaller crystallinity compared to that under native vegetation due to K removal from the interlayer space.

Even if these results cannot be generalized to all Ferralsols, they clearly show the importance of non-exchangeable pools corresponding to non-exchangeable K located within the interlayer space of 2:1 phyllosilicates in the supply of K to plants in agricultural production systems.

7. Conclusion

Since the earliest studies, 2:1 phyllosilicates identified in Ferralsols, as defined in the IUSS Working Group WRB (2022) or equivalent soils in other soil classification systems, were mainly characterized using XRD by a peak at ~ 1.4 nm which did not expend upon ethylene glycol solvation and collapse to a broad peak between 1.2 and 1.0 nm upon heating around 300°C. It was shown that these 2:1 phyllosilicates, often interpreted as hydroxy-Al interlayered minerals because their XRD features were similar to those observed for 2:1:1 phyllosilicates with incomplete Al-hydroxy interlayering – particularly in the studies performed during the last two decades – were mainly present in the fine-silt and coarse-clay fraction. They were initially interpreted as HIV resulting from the weathering of muscovite present in the underlying parent material, followed by aluminization of the interlayer space of the resulting vermiculite. An alternative hypothesis, in soils developed on mafic parent materials where muscovite is absent, is that these 2:1 phyllosilicates are hydroxy-Al interlayered smectites, resulting from the aluminization of smectites neoformed within the saprolite.

Although their possible presence in very small proportions has gradually been integrated, without this presence being a diagnostic criterion, into the definition of Ferralsols (IUSS Working Group WRB, 2022) or in equivalent soils according to other soil classification systems, their origin remains debated. Interpreted by some authors as resulting from neoformation processes within the soil, others, more numerous, interpret them as being relict minerals having resisted weathering processes. Most authors interpret their presence as being allochthonous relict minerals, that is, inherited from deeper layers and transported upward, primarily by the burrowing activity of social insects, especially termites. This is supported by observations in termite mounds, where construction materials often contain 2:1 phyllosilicates, indicating sampling from the saprolite or deep Ferralsol horizons. Due to their high resistance to weathering, these minerals persist for long periods in the horizons where they have been transported by biological activity. In this interpretation, the transport processes from the saprolite or deep horizons somehow seeded the entire thickness of the Ferralsol with 2:1 minerals, which, being relatively resistant to weathering processes, are still observable today and present different degrees of aluminization and desilication. This hypothesis appears to be the most probable, as it is difficult to envisage that 2:1 phyllosilicates still present in the surface horizons could be relict minerals having resisted the weathering process in these soils which developed for several hundred thousand years, or even more than a million years. A formation thanks to neogenesis processes is not easy to envisage in soils dominated by desilication processes and the neoformation of aluminum and iron oxyhydroxides. However, a few studies showed that even if desilication leads to smectite and vermiculite dissolution, relict neoformed 2:1 clays can persist for very long time.

Among the consequences of the presence of 2:1 phyllosilicates in Ferralsols are those of the potassium reserve they can represent and the availability of this potassium for the mineral nutrition of plants. Several studies have indeed focused on the availability of potassium possibly present in the interlayer space of these 2:1 phyllosilicates. These studies showed that 5 to 30% of the total potassium present in these 2:1 minerals is exchangeable when the Ferralsols considered are still under native vegetation. Once cultivated, this exchangeable potassium reserve is exhausted within a few years and the flows from the remaining potassium stock are very low.

Interpretations of 2:1 phyllosilicates origin and distribution in Ferralsols remain limited by the scope of the studies which rarely covered the entire soil thickness, from the saprolite to the surface horizons. Future research should compare field observations with hypotheses derived from our understanding of weathering processes within the geochemical contexts prevalent in Ferralsols, while explicitly accounting for parent material composition. Two distinct geochemical contexts already emerge: Ferralsols developed on mafic rocks (e.g., basalt, gabbro) versus those on felsic substrates (e.g., granite, rhyolite).

Finally, if, as suggested by many authors, the activity of social insects, such as that of termites, plays a significant role in the vertical transport of material, it will be necessary to better understand and quantify this bioturbation not only within Ferralsols, but broadly within ferralitic soils including Lixisols and Acrisols.

CRediT authorship contribution statement

Ary Bruand: Writing – review & editing, Writing – original draft, Methodology, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Michel Brossard:** Writing – review & editing, Conceptualization. **Laurent Caner:** Writing – review & editing, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could influence the work reported in this paper.

Acknowledgements

The authors acknowledge financial support from the LabEx VOLTAIRE (ANR-10-LABX-100-01) and the EquipEx PLANEX (ANR-11-EQPX-0036) projects.

Data availability

Data will be made available on request.

References

AFES, 2009. Référentiel pédologique 2008 (D. Baize and M.C. Girard coord.). Quae éditions, 432 p.

Almeida, C.C., Fontes, M.P.F., Dias, A.C., Pereira, T.T.C., Ker, J.C., 2021. Mineralogical, chemical and electrochemical attributes of soils. Sci. Agric. 78 (6), e20200071. https://doi.org/10.1590/1678-992X-2020-0071.

Alves, M.J.F., Melo, V.F., Reissmann, C.B., Kaseker, J.F., 2013. Reserva mineral de potássio em latossolo cultivado com *Pinus taeda* L. R. Bras. Ci. Solo 37, 1599–1610. https://doi.org/10.1590/S0100-06832013000600016.

Antonello, A.A., 1988. Mineralogy of the deferrified clay fraction in B horizon of pedons of the Eighth International Soil Classification Workshop. In: Classification, Characterization and Utilization of Oxisols, Part 1: Papers (eds. F. H. Beinroth, M. N. Camargo and H. Eswaran). Proceedings of the Eighth International Soil Classification Workshop, Brazil, 12 to 13 May 1986, SNLCS-Embrapa, Soil Management Support Services and Soil Conservation Service–United States Department of Agriculture, University of Puerto Rico. pp. 109-138.

Arkcoll, D.B., Goulding, K.W.T., Hughes, J.C., 1985. Traces of 2:1 layer-silicate clays in Oxisols from Brazil, and their significance for potassium nutrition. J. Soil Sci. 36, 123–128. https://doi.org/10.1111/j.1365-2389.1985.tb00317.x.

Azevedo, A.C., Kämpf, N., Bohnen, H., 1996. Alterações na dinamâmica evolutiva de Latossolo bruno pela calagem. Rev. Bras. Ciênc. Solo 20, 191–198.

Aurousseau, P., Curmi, P., Bouille, S., Charpentier, S., 1983. Les vermiculites hydroxy-alumineuses du Massif Armoricain (France). Approche minéralogique, microanalytique et thermodynamique. Geoderma 31, 17–40. https://doi.org/10.1016/0016-7061(83)90081-2.

Bain, D.C., 1977. The weathering of ferruginous chlorite in a podzol from Argyllshire, Scotland. Geoderma 17, 193–208. https://doi.org/10.1016/0016-7061(77)90050-7.

Barnhisel, R.I., Bertsch, P.M., 1989. Chlorites and hydroxy-interlayered vermiculite and smectite. In: Minerals in soil environments (Eds. J.B. Dixon and S.B. Weed) 1, 729–788. https://doi.org/10.2136/sssabookser1.2ed.c15.

Bartoli, F., Burtin, G., Herbillon, A.J., 1991. Disaggregation and clay dispersion of Oxisols: Na resin, a recommended methodology. Geoderma 49, 301–317. https://doi-org.insu.bib.cnrs.fr/10.1016/0016-7061(91)90082-5.

Beinroth, F.H., 1982. Some highly weathered soils of Purto Rico, 1. Morphology, formation, and classification. Geoderma 27, 1–73. https://doi-org.insu.bib.cnrs.fr/10.1016/0016-7061(82)90047-7.

Bertolazi, V.T., Inda, A.V., Caner, L., Martins, A.P., Vaz, M.A.B., Bonnet, M., Anghinoni, I., Carvalho, P.C.F., 2017. Impact of an integrated no-till soybean-beef cattle production system on Oxisol mineralogy in southern Brazil. Appl. Clay Sci. 149, 67–74. https://doi.org/10.1016/j.clay.2017.08.028.

Boyer, P., 1973. Action de certains termites constructeurs sur l'évolution des sols tropicaux. Annales Des Sciences Naturelles, Zoologie, Paris 15, 329–498.

Brito Galvão, T.C.D., Schulze, D.G., 1996. Mineralogical properties of a collapsible lateritic soil from Minas Gerais, Brazil, Soil Sici. Soc. Am. J. 60, 1969–1978. https://doi.org/10.2136/sssaj1996.03615995006000060050x.

Bruand, A., Cousin, I., Nicoulland, B., Duval, O., Bégon, J.C., 1996. Backscattered electron scanning images of soil porosity for analyzing soil compaction around roots. Soil Sci. Soc. Am. J. 60, 895–901. https://doi.org/10.2136/sssaj1996.03615995006000030031x.

Bruand, A., 2025. Social insects behind the microgranular structure of Ferralsols: consequences for their physical fertility. Pedosphere 35, 17–19. https://doi.org/10.1016/j.pedsph.2023.12.011.

Bruand, A., Reatto, A., 2022. Morphology, chemical composition and origin of 2:1 phyllosilicates in Bw horizons of latosols of the Brazilian Central Plateau: contribution to the discussion of the microgranular structure origin. C.R. Geosc 354, 159–185. https://doi.org/10.5802/crgeos.123.

Bruand, A., Reatto, A., Martins, E.D.S., 2022. Allochthonous material originating from saprolite as a marker of termite activity in Ferralsols. Sci. Rep. 12, 17193. https://doi.org/10.1038/s41598-022-21613-6.

Bruand, A., Reatto, A., Brossard, M., Jouquet, P., Martins, E.D.S., 2023. Long-term activity of social insects responsible for the physical fertility of soils in the tropics. Sci. Rep. 13, 12337. https://doi.org/10.1038/s41598-023-39654-w.

Bruand, A., Brossard, M., Jouquet, P., Reatto, A., Garnier, J., Quintinelli, J.M., Martins, E.S., 2024. – Presence of potassium-bearing 2:1 phyllosilicates in B horizons of Ferralsols: consequences for total and exchangeable potassium content. Geoderma 448, 116949. https://www.sciencedirect.com/science/article/pii/S0016706124001782.

Buol, S.W., Eswaran H., 1999. Oxisols. Advances in Agronomy, 68, Academic Press, 151–195. https://doi.org/10.1016/S0065-2113(08)60845-7.

Buringh, P., 1970. Introduction to the study of soils in the tropical and subtropical regions. Pudoc, Wageningen, p. 100.

Camargo, M.N., Jacomine, P.K.T, Carvalho, A.P., J. Olmos, I.L., 1988. The Brazilian classification of Latosols. In: Classification, Characterization and Utilization of Oxisols, Part 1: Papers (eds. F.H. Beinroth, M.N. Camargo and H. Eswaram). Proceedings of the Eighth International Soil Classification Workshop, Brazil, 12 to 13 May 1986, SNLCS-Embrapa, Soil Management Support Services and Soil Conservation Service–United States Department of Agriculture, University of Puerto Rico. pp. 190-199.

Caner, L., Radtke, L.M., Vignol-Lelarge, L.M., Inda Jr, A.V., Bortoluzzi, E.C., Mexias, A.S., 2014. Basalt and rhyo-dacite weathering and soil clay formation under subtropical climate in southern Brazil. Geoderma 235–236, 100–112. https://doi.org/10.1016/j.geoderma.2014.06.024.

Chiapini, M., Nascimento, D.L., Santos, T.A., Marques, K.P.P., Rodrigues, B.M., Camargo, P.B., Cooper, M., Vidal-Torrado, P., 2025. Bioturbation in very deep tropical Ferralsols: a micromorphological study of biomantles. Catena 256, 109084. https://doi-org.insu.bib.cnrs.fr/10.1016/j.earscirev.2023.104650.

Chiapini, M., Schellekens, J., de Oliveira, J.C., Jr., Calegari, M.R., Vidal-Torrado, P., 2023. Pedogenesis in very deep autochthonous Ferralsols of the Parana Igneous Province (Brazil). Catena 224, 106981. https://www.10.1016/j.catena.2023.106981.

Clay, N.A., Yanoviak, S.P., Kaspari, M., 2014. Short-term sodium inputs attract microbi-ditrivores and their predators. Soil Biol. Biochem. 75, 248–253. https://doi.org/10.1016/j.soilbio.2014.04.021.

Cline, M.G., Buol, S.W., 1973. Soils of the Central Plateau of Brazil and extension of results of field research conducted near Planaltina, Federal District. Agronomy Mineo, 73-17, Cornell University, Ithaca, NY, 43p.

Classification Des Sols. Orléans, 1967, 96p.

Cornelis, J.T., Delvaux, B., 2016. The functional role of silicon in plant biology. Soil processes drive the biological silicon feedback loop. Funct. Ecol. 30, 1298–1310. https://doi.org/10.1111/1365-2435.12704.

Costa, A.C.S., Souza Junior, I.G., Canton, L.C., Gil, L.G., Figueiredo, R., 2020. Contribution of the chemical and mineralogical properties of sandy-loam tropical soils to the cation exchange capacity. Rev. Bras. Cienc. Solo 44, e200019. https://doi.org/ 10.36783/18069657rbcs20200019.

Cunha, A.M., Fontes, M.P.F., Lani, J.L., 2017. Mineralogical and chemical attributes of soils from the Brazilian Atlantic Forest domain. Sci. Agric. 76, 82–92. https://doi.org/10.1590/1678-992X-2017-0109.

Curi, N., Franzmeier, D., 1984. Toposequence of Oxisols from Central Plateau of Brazil. Soil Sci. Soc. Am. J. 48, 341–346. https://doi.org/10.2136/sssaj1984.03615995004800020024x.

Darunsontaya, T., Suddhiprakarn, A., Kheruenromme, I., Gilkes, R.J., 2010. The kinetics of potassium release to sodium tetraphenylboron solution from the clay fraction of highly weathered soils. Appl. Clay Sci. 50, 376–385. https://doi.org/10.1016/j.clay.2010.09.001.

Darunsontaya, T., Suddhiprakarn, A., Kheruenromme, 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. https://doi.org/10.1016/j.geoderma.2011.10.002.

Delvaux, B., 1990. Surface Properties and Clay Mineralogy of Hydrated Halloysitic Soil Clays. I: Existence of Interlayer K+ specific Sites. Clay Miner. 25, 129–139. https://doi.org/10.1180/claymin.1990.025.2.01.

Dias, N.M.P., Gonçalves, D., Leite, W.C., Brinati, A.M., Saab, S.C., Pires, L.F., 2013. Morphological characterization of soil fraction in nanometric scale. Powder Technol. 241, 36–42. https://doi.org/10.1016/j.powtec.2013.03.006.

Dowding, C.E., Fey, M.V., 2007. Morphological, chemical and mineralogical properties of some manganese-rich oxisols derived from dolomite in Mpumalanga province, South Africa. Geoderma 141, 23–33. https://doi.org/10.1016/j.geoderma.2007.04.024.

Dymond, J., Biscaye, P.E., Rex, R.W., 1974. Eolian origin of Mica in Hawaiian soils. Geological Society of America Bulletin, 85, 3–40. https://doi.org/ 10.1130/0016-7606(1974)85.

Embrapa, 2018. Brazilian Soil Classification System. 5th Edition, Brasilia-DF, 388 pp.

Embrapa, 2006. Sistema Brasileiro de Classificação de Solos. Empresa Brasileira de Pesquisa Agropecuária, Rio de Janeiro-RJ, p. 306.

Eschenbrenner, V., 1986. Contribution des termites à la micro-agrégation des sols tropicaux. Cahiers ORSTOM, Série Pédologie 22, 397–408.

Escobar, E.H., Delmatte, J.L.I., Moniz, A.C., 1973. Gênese e classificação de alguns solos da Baia do Ribeirão Tijuco Preto, Municipio de Rio das Pedras, SD. I. – Análise mineralógica quantitativa da fração argila. Revista Científica Do Instituto Agronômico Do Estado De São Paulo 32, 93–116.

Eswaran, H., de Coninck, F., 1971. Clay mineral formation in basaltic soils in tropical environments. Pédologie 21 (2), 181–210.

FAO, 1990. Guidelines for soil description, 3rd edn. FAO/ISRIC, Rome.

FAO, 1988. FAO-UNESCO Soil Map of the World. Revised Legend with correction. Reprinted with correction, as technical Paper 20, ISRIC, Wageningen, 1994, Rome, FAO.

FAO-UNESCO, 1974. Soil Map of the World. 1:500 000. Vol. 1, Legend, Paris, UNESCO.

Farina, M.P.W., Le Roux, J., 1974. The relationship between exchangeable potassium and soil moisture in some important Natal Soils. Fertilizer Society of South Africa Journal 1, 39–42.

Ferreira, C.A., Silva, A.C., Torrado, P.V., Rocha, W.W., 2010. Genesis and classification of Oxisols in a highland toposequence of the upper Jequituinhonha Valley (MG). R. Bras. Ci. Solo 34, 195–209. https://doi.org/10.1590/S0100-06832010000100020.

Fey, M.V., 1974. Characteristics of sesquioxidic soils. In: PhD, Department of Soil Science and Agrometeorology. University of Natal, p. 149p.

Firmano, R.F., Melo, V.F., Montes, C.R., de Oliveira, A., Castro, C., Alleoni, L.R.F., 2020. Potassium reserves in the clay fraction of a tropical soil fertilized for three decades. Clays and Clay Min. 68, 237–249. https://doi.org/10.1007/s42860-020-00078-6.

Fox, R.L., 1982. Some highly weathered soils of Puerto Rico, 3. Chemical Properties. Geoderma 27, 139–176. https://doi-org.insu.bib.cnrs.fr/10.1016/0016-7061(82)90049-0.

Georgiadis, A., Dietel, J., Dohrmann, R., Rennert, Th., 2020. What are the nature and formation conditions of hydroxy-interlayered minerals (HIMs) in soil? J. Plant Nut. Soil Sci. 183, 12–26. https://doi.org/10.1002/jpln.201900283.

He, Y., Li, D.C., Velde, B., Yang, Y.F., Huang, C.M., Gong, Z.T., Zhang, G.L., 2008. Clay minerals in a soil chronosequence derived from basalt on Hainan Island, China and its implication for pedogenesis. Geoderma 148, 206–212. https://doi.org/10.1016/j.geoderma.2008.10.007.

Herbillon, A.J., 1980. Mineralogy of Oxisols and oxic materials. In: Theng, B.K.G. (Ed.), Soils with Variable Charge. New Zealand Society of Soil Science, Palmerson North, pp. 109–126.

Göedert, W.J., Lobato, E., 1988. Agronomic considerations of modern agriculture on oxisols. In: Proceedings of the Eighth International Soil Classification Workshop, Brazil 12-23 May 1986, Part 1 (E.H. Beinroth, M.N. Carmargo and H. Eswaran eds.), SNLCS-EMBRAPA, SMSS-SCS-USDA, Washington, DC. 203 – 210.

Herbillon, A.J., 1988. Chemical composition of weatherable minerals present in the diagnostic horizon of low activity clay soils. In: Classification, Characterization and Utilization of Oxisols, Part 1: Papers (eds. F. H. Beinroth, M. N. Camargo and H. Eswaram). Proceedings of the Eighth International Soil Classification Workshop, Brazil, 12 to 13 May 1986, SNLCS-Embrapa, Soil Management Support Services and Soil Conservation Service–United States Department of Agriculture, University of Puerto Rico. pp. 39-48.

Herbillon, A.J., Gallez, A., A. S. R. Juo A.S.R., 1977. Characteristics of silica sorption and solubility as parameters to evaluate the surface properties of tropical soils: II. the Index of Silica Saturation. Soil Sci. Soc. Am. J. 47, 1247–1251. https://doi.org/10.2136/sssaj1977.03615995004100060028x.

Hummes, A.P., Inda, A.V., Olk, D.C., Bortoluzzi, E.C., 2024. Mineral changes in the rhizospheres of conifer plantations for a weathered subtropical soil. Soil Sci. Soc. Am. J. 88, 1463–1478. https://doi.org/10.1002/saj2.20682.

ICOMOX, 1988. Classification, characterization and utilization of Oxisols. Proceedings of the Eighth International Soil Classification Workshop, Brazil 12-23 May 1986, Part 1 and Part 2 (E.H. Beinroth, M.N. Carmargo and H. Eswaran eds.), Management Support Services, US Dep. Agric., Washington, DC.

Inda, A.V., Torrent, J., Barrón, V., Bayer, C., 2010. Aluminum hydroxy-interlayered minerals and chemical properties of a subtropical Brazilian Oxisol under no-tillage and conventional tillage. R. Bras. Ci. Solo 34, 33–41. https://doi.org/10.1590/S0100-06832010000100004.

ISSS-IRSIC FAO, 1988. World Reference Base for Soil Resources. World Resources Report, 84 Rome, FAO 88.

IUSS Working Group WRB, 2022. World Reference Base for Soil Resources. International soil classification system for naming soils and creating legends for soil maps, 4th Edition. International Union of Soil Sciences (IUSS), Vienna, Austria.

Jackson, M.L., 1962. Interlayering of expansible layer silicates in soils by chemical weathering. Clays Clay Miner. 11, 29–46. https://doi.org/10.1346/CCMN.1962.0110104.

Jones, R.C., Hudnall, W.H., Sakai, W.S., 1982. Some highly weathered soils of Puerto Rico; 2, Mineralogy. Geoderma 27, 75–137. https://doi.org/10.1016/0016-7061(82)90048-9.

Jouquet, P., Botinelli, N., Shanbhag, R.R., Bourguignon, T., Traoré, S., Abbasi, S.A., 2016. Termites: the neglected soil engineers of tropical soils. Soil Sci. 181, 157–165. https://doi.org/10.1097/SS.0000000000000119.

Jouquet, P., Bruand, A., 2023. Bioturbation as a means to circumvent sodium limitation by termites? Biol. Fertil. Soils 59, 567–570. https://doi.org/10.1007/s00374-023-01752-2.

Jouquet, P., Chintakunta, S., Bottinelli, N., Subramanian, S., Caner, L., 2016. The influence of fungus-growing termites on soil macro and micro-aggregates stability varies with soil type. Appl. Soil Ecol. 101, 117–123. https://doi.org/10.1016/j.apsoil.2016.02.001.

Jouquet, P., Guilleux, N., Caner, L., Chintakunta, S., Ameline, M., Shanbhag, R.R., 2016. Influence of soil pedological properties on termite mound stability. Geoderma 262, 45–51. https://doi.org/10.1016/j.geoderma.2015.08.020.

Jouquet, P., Jamoteau, F., Majumdar, S., Podwojewski, P., Nagabovanalli, P., Caner, L., Barboni, D., Meunier, J-D., 2020. The distribution of silicon in soils influenced by termite bioturbation in South Indian forest soils. Geoderma 372, 114362. https://doi.org/0.1016/j.geoderma.2020.114362.

Juo, A.S.R., 1980. Mineralogical characteristics of Alfisols and Ultisols. In: Theng, B.K.G. (Ed.), Soils with Variable Charge. New Zealand Society of Soil Science, Palmerson North, pp. 69–86.

Kalima, C. Spaargaren, O.C., 1987. Oxisols of Zambia. Soil Survey Unit, Research Branch, Department of Agriculture, Soil Bulletin, 21, 12p.

Kämpf, N., Azevedo, A.C., Costa, M.I., 1995. Estrura básica de argilomineral 2:1 com hidróxi-Al entrecamadas em Latossolo Bruno do Rio Grande do Sul. R. Bras. Ciênc. Solo 19, 185–190.

Karathanasis, A.D., Adams, F., Hajek, B.F., 1983. Stability relationships in kaolinite, gibbsite, and Al-hydroxyinterlayered vermiculite soil systems. Soil Sci. Soc. Am. J. 47, 1247–1251. https://doi.org/10.2136/sssaj1983.03615995004700060036x.

Karathanasis, A.D., 2002. Mineral equilibria in environmental soil systems. In: Soil mineralogy with environmental applications (Eds.: J.B. Dixon and D.G. Schulze) 7, 109–151. https://doi/10.2136/sssabookser7.c4.

Kaspari, M., Clay, N.A., Donoso, D.A., Yanoviak, S.P., 2014. Sodium fertilization increases termites and enhances decomposition in an amazonian forest. Ecology 95, 795–800. https://doi.org/10.1890/13-1274.1.

Kaspari, M., Yanoviak, S.P., Dudley, R., Yuan, M., Clay, N.A., 2009. Sodium shortage as a constraint on the carbon cycle in an inland tropical rainforest. Proc. Nat Ac Sci. 106, 19405–19409. https://doi.org/10.1073/pnas.0906448106.

Ker, J.C., 1997. Latossolos Do Brasil: Uma Revisão. Geonomos 5 (1), 17–40.

Khawmee, K., Suddiprakarn, A., Kheoruenromme, I., Singh, B., 2013. Surface charge properties of kaolinite from Thai soils. Geoderma 192, 120–131. https://doi.org/10.1016/j.geoderma.2012.07.010.

Kitagawa, Y., Nakao, A., Tanaka, R., Takeda, A., Yamada, D., Evrard, O., Yanai, J., 2024. Relative importance of Asian-dust-derived micas estimated from oxygen isotopic analysis of fine quartz on specific retention of radiocesium in Andosols in Tohoku Region, Japan. Soil Sci. Plant Nutr., 70, 375–386. https://doi.org/ 10.1080/00380768.2024.2387732.

Korchagin, J., Bortoluzzi, E.C., Moterle, D.F., Petry, C., Caner, L., 2019. Evidences of soil geochemistry and mineralogy changes caused by eucalyptus rhizosphere. Catena 175, 132–143. https://doi.org/10.1016/j.catena.2018.12.001.

Kurtz, A.C., Derry, L.A., Chadwick, O.A., 2001. Accretion of asian dust to hawaiian soils : Isotopic, elemental, and mineral mass balances. Geochimica and Cosmochimica Acta 65, 1971–1983. https://doi.org/10.1016/S0016-7037(01)00575-0.

Lelong, F., Millot, G., 1966. Sur l'origine des minéraux micacés des altérations latéritiques. Diagenèse régressive - Minéraux en transit. Sciences Géologiques, Bulletins et Mémoires 19, 271–286.

Lepsch, I.F., Buol, S.W., 1974. Investigations in a Oxisol-Ultisol toposequence in San Paulo State. Brazil. Soil Sci. Soc. Am. J. 38, 491–496. https://doi.org/10.2136/sssaj1974.03615995003800030031x.

Le Roux, J., 1973. Quantitative clay mineralogical analysis of Natal Oxisols. Soil Sci. 115, 137–144.

Li, K., Shi, Y., Nkoh, J.N., Jiang, J., Xu, R., 2024. Effect of coordination structure of aluminum on its activation from minerals and Oxisols during their acidification. Pedosphere 34, 916–928.

Lopes, T.C.S., Portela, J.C., Batista, R.O., Bandeira, D.J.C., Leite, I.O., Ramalho, L.B., Gondim, J.E.F., Costa, J.D., Gurgel, M.T., Souza, C.M.M., Silva, E.F., Souza, E.R., de Oliveira, F.H.T., Miranda, N.O., Silva, Sa., F.V., 2022. Clay fraction mineralogy and structural soil attributes of two soil classes under the semi-arid climate of Brazil. Land 11, 2192. https://doi.org/10.3390/land11122192.

Lucas, Y., Luizão, J., Chauvel, A., Rouiller, J., Nahon, D., 1993. The relation between biological activity of the rain forest and mineral composition of soils. Science 260, 521–523. https://doi.org/10.1126/science.260.5107.521.

Lyngsie, G., Awadzi, T., Breuning-Madsen, H., 2011. Origin of Harmattan dust settled in Northern Ghana – Long transported or local dust? Geoderma 167, 351–359. https://doi.org/10.1016/j.geoderma.2011.07.026.

Macedo, J., Bryant, R.B., 1987. Morphology, mineralogy, and genesis of a hydrosequence of Oxisols in Brazil. Soil Sci. Soc. Am. J. 51, 690–698. https://doi.org/10.2136/sssaj1987.03615995005100030025x.

Mafra, A.L., Miklós, A.A.W., Volkoff, B., Melfi, A.J., 2002. Pedogênese numa seqüência Latossolo-Espodossolo na região do alto Rio Negro. Amazonas. r. Bras. Ci. Solo 26, 381–394.

Mancini, M., Silva, S.H.G., Hartemink, A.E., Zhang, Y.K., de Faria, A.J.G., Silva, F.M., Inda, A.V., Demattê, J.A.M., Curi, N., 2021. Formation and variation of a 4.5 m deep Oxisol in southeastern Brazil. Catena 206, 105492. https://doi.org/10.1016/j.catena.2021.105492.

Manning, D.A.C., 2010. Mineral sources of potassium for plant nutrition. A Review. Agron. Sustain. Dev. 30, 281–294. https://doi.org/10.1051/agro/2009023.

Maquere, V., 2008. Dynamics of mineral elements under a fast-growing Eucalyptus plantation in Brazil. Implications for soil sustainability. University of Sao Paulo and Agro Paris Tech, p. 375p. PhD thesis.

Marques, F.A., Calegari, M.R., Vidal-Toradol, P., Buurman, P., 2011. Relationship between soil oxidizable carbon and physical, chemical and mineralogical properties of Umbric Ferralsols. B. Bras. Ci. Solo 35, 25–40. https://doi.org/10.1590/S0100-06832011000100003.

Martins, R., Melo, V.F., Serrat, B.M., 2004. Reserva mineral de potássio em solos do Campos Gerais, Estado do Paraná. Revista Ceres 51, 521–533.

Melfi, A.J., Pédro, G., 1977. Estudo geoquímico dos solos e formações superficiais do Brasil. Parte 1 – Caracterização e repartição dos principais tipos de evolução pedogeoquímica. R. Bras. Geociências 7, 271–286.

Melfi, A.J., Pédro, G., 1978. Estudo geoquímico dos solos e formações superficiais do Brasil. Parte 2 – Considerações sobre os mecanismos geoquímicos envolvidos na alteração superficial e sua repartição no Brasil. R. Bras. Geociências 8, 11–22.

Melo, G.W., Meurer, E.J., Pinto, L.F.S., 2004. Fontes de potássio em solos distroférricos cauliníticos originados de basalto no Rio Grande do Sul. R. Bras. De Ciênc. Solo 28, 597–603.

Møberg, J.P., Esu, I.E., 1991. Characteristics and composition of some savanna soils in Nigeria. Geoderma 48, 113–129. https://doi-org.insu.bib.cnrs.fr/10.1016/0016-7061(91)90011-H.

Moniz, A.C., 1967. Quantitative mineralogical analysis of Brazilian soils derived from basic rocks and slate. MS Thesis, Soil Department, University of Wisconsin, Madison, 74p.

Moterle, D.F., Bortoluzzi, E.C., Kaminski, J., Rheinheimer, D.S., Caner, L., 2019. Does Ferralsol clay mineralogy maintain potassium long-term supply to plants? Revista Brasileira De Ciência Do Solo 43, e0180166. https://doi.org/10.1590/18069657rbcs20180166.

Moura Filho, W., Buol, S.W., 1972. Studies of a Latosol Roxo (Eutrustox) in Brazil: description, setting and characterization. Experientiae 13, 201–234.

Muchena, F.N., Wokabi, S.M., 1988. The red soils of Kenya. Their occurrence, distribution and major characteristics. In: The red soils of East and Southern Africa: proceedings of an international symposium, Harare, Zimbabwe, 243-27 February 1986, Nyamapfene K., Hussein J. and Asumadu K. (eds), IDRC, Ottawa, Canada, 122–149.

Mujinya, B.B., Mees, F., Erens, H., Dumon, M., Baert, G., Boeckx, P., Ngongo, M., van Ranst, E., 2013. Clay composition and properties in termite mounds of the Lubumbashi area, D.R. Congo. Geoderma 192, 304–315. https://doi.org/10.1016/j.geoderma.2012.08.010.

Nakao, A., Uno, S., Yanai, J., Kubotera, H., Tanaka, R., Root, R.A., Kosaki, T., 2021. Distance-dependence from volcano for asian dust inclusions in Andosols: a key to control soil ability to retain radiocesium. Geoderma 385, 114889. https://doi.org/10.1016/j.geoderma.2020.114889.

Nakao, A., Sugihara, S., Maejima, Y., Tsukada, H., Funakawa, S., 2017. Ferralsols in the Cameroon plateaus, with a focus on the mineralogical control on their cation exchange capacities. Geoderma 285, 206–2016. https://doi.org/10.1016/j.geoderma.2016.10.003.

Nascimento, D.L., Chiapini, M., Vidal-Torrado, P., Phillips, J.D., Ladeira, F.S.B., Machado, D.F.T., Da Silva, C.R., Valezio, E.V., 2024. The underestimated role of leaf-cutting ants in soil and geomorphological development in neotropical America. Earth Sci. Rev. 248, 104650. https://doi.org/10.1016/j.earscirev.2023.104650.

Ndayiragije, S., Delvaux, B., 2003. Coexistence of allophane, gibbsite, kaolinite and hydroxy-Al-interlayered 2:1 clay minerals in a perudic Andosol. Geoderma 117, 203–214. https://doi.org/10.1016/S0016-7061(03)00123-X.

Ndzana, G.M., Huang, L., Zhang, Z., Zhu, J., Liu, F., Bhattacharyya, R., 2019. The transformation of clay minerals in the particle size fractions of two soils from different latitude in China. Catena 175, 317–328. https://doi.org/10.1016/j.catena.2018.12.026.

Ogawa, K., Phetchawee, S., Suriyapan, O., 1981. Clay minerals in some upland soils from Thailand. Soil Sci. Plant Nut. 27, 73–81. https://doi.org/10.1080/00380768.1981.10431256.

de Oliveira, L.B., Ferreira, M.G.V.X., Marques, F.A., 2004. Characterization and classification of two soils derived from basic rocks in Pernambuco State coast, Northeast Brazil. Sci. Agric. 61, 615–625. https://doi.org/10.1590/S0103-90162004000600009.

de Oliveira, J.S., Inda, A.V., Barron, V., Torrent, J., Tiecher, T., Camargo, F.A.D., 2020. Soil properties governing phosphorus adsorption in soils of Southern Brazil. Geoderma Reg. 22, e00318. https://doi.org/10.1016/j.geodrs.2020.e00318.

Ortigao, J.A.R., Kochen, R., Farias, M.M., Assis, A., 1996. Tunnelling in Brasilia porous clay. Can. Geotech. J. 33, 565–573. https://doi.org/10.1139/t96-082-304.

Pacheco, A.A., Ker, J.C., Schaefer, G.E.G.R., Fontes, M.P.F., Andrade, F.V., Martins, E.S., Oliveira, F.S., 2018. Mineralogy, micromorphology and genesis of soils with varying drainage along a hillslope on granitic rocks of a Atlantic Forest biome, Brazil. Revista Brasileira De Ciência Do Solo 42, e0170291. https://doi.org/10.1590/18069657rbcs20170291.

Paisani, J.C., Pontelli, M.E., Corrêa, A.C.D., Rodrigues, R.A.R., 2013. Pedogeochemistry and micromorphology of oxisols - a basis for understanding etchplanation in the Araucarias Plateau (Southern Brazil) in the Late Quaternary. J. S. Am. Earth Sci. 48, 1–12. https://doi.org/10.1016/j.jsames.2013.07.011.

Pédro, G., 1968. Distribution des principaux types d'altération chimique à la surface du globe. Rev. Géogr. Phys. Géol. Dyn. X 457–470.

Pereira, T.T.C., Ker, J.C., Schaeffer, C.E.G.R., Barros, N.F., Neves, J.C.L., Almeida, C.C., 2010. Genesis of latosols and cambisols developed from pelitic rocks of the Bambui group, Minas Gerais state. Brazil. r. Bras. Ci. Solo 34, 1283–1295. https://doi.org/10.1590/S0100-06832010000400026.

Poss, R., Fardeau, J.C., Saragoni, H., Quantin, P., 1991. Potassium release and fixation in Ferralsols (Oxixols) from Southern Togo. J. Soil Sci. 42, 649–660. https://doi.org/10.1111/j.1365-2389.1991.tb00111.x.

Pincus, L.N., Ryan, P.C., Huertas, F.J., Alvarado, G.E., 2017. The influence of soil age and regional climate on clay mineralogy and cation exchange capacity of moist tropical soils: a case study from Late Quaternary chronosequences in Costa Rica. Geoderma 308, 130–148. https://doi.org/10.1016/j.geoderma.2017.08.033.

Prospero, J.M., Glaccum, R.A., Nees, R.T., 1981. Atmospheric transport of soil dust from Africa to South America. Nature 289, 570–572.

Reatto, A., Martins, E.S., Guimarães, E.M., Spera, S.T., Correia, J.R., 2000. Variabilidade mineralógica de latossolos da área da Embrapa Cerrados em relação aos do Bioma Cerrado. BP Embrapa Cerrados. 20, 1–29.

Reatto, A., Bruand, A., Silva, E.M., Martins, E.S., Brossard, M., 2007. Hydraulic properties of the diagnostic horizon of Latosols of a regional toposequence across the Brazilian Central Plateau. Geoderma 139, 51–59. https://doi.org/10.1016/j.geoderma.2007.01.003.

Reatto, A., Bruand., A., Martins, E.S., Muller, F., Silva, E.M., Carvalho Jr, O.A. and Brossard, M, 2008. Variation of the kaolinite and gibbsite content at regional and local scale in the Latosols of the Brazilian Central Plateau. C.R. Geoscience 340, 741–748. https://doi.org/10.1016/j.crte.2008.07.006.

Reatto, A., Bruand, A., Martins, E.S., Muller, F., Silva, E.M., Carvalho Jr., O.A., Brossard, M., Richard, G., 2009. Development and origin of the microgranular structure in Latosols of the Brazilian Central Plateau: significance of texture, mineralogy, and biological activity. Catena 76, 122–134. https://doi.org/10.1016/j.catena.2008.10.003.

Reatto, A., Bruand, A., Guilherme, L.R.G., Martins, E.S., Medrado, E., Brossard, M., Muller, F., 2010. Geochemical processes in Latosols on the geomorphic surfaces from Brazilian Central Plateau. 19Th World Congress of Soil Science, Soil Solutions for a Changing World.

Robert, M., Veneau, G., 1979. Stabilité des mineraux phylliteux 2/1 en conditions acides. Rôle de la composition octaédrique. In : Proceedings of the VI International Clay Conference 1978, organized by the Clay Minerals Group, Mineralogical Society, London, under the auspices of Association Internationale pour l'Etude des Argiles. 10-14 July 1978,Oxford (Eds. M.M. Mortland and V.C. Farmer). 385–394.

Rodrigues, Netto A., 1996. Influencìa da mineralogia da fracão argila sobre propriedades fisico-químicas de solos Brasileiros. Federal University of Viçosa, Brasil. MSc thesis.

Rolim Neto, F.C., Schaefer, C.G.G.R., Fernandes, E.I., Corrêa, M.M., da Costa, L.M., Parahyba, R.D.V., Guerra, S.M.S., Heck, R., 2009. Topolitossequências de solos do alto Paranaíba: atributos físicos, químicos e mineralógicos. R. Bras. Ciênc. Solo 33, 1795–1809.

Ross, G.J., Wang, C., Ozkan, A.I., Rees, H.W., 1982. Weathering of chlorite and mica in a New Brunswick podzol developed on till derived from chlorite-mica schist. Geoderma 27, 255–267. https://doi.org/10.1016/0016-7061(82)90034-9G.

Ryan, P.C., Huertas, F.J., Hobbs, F.W.C., Pincus, L.N., 2016. Kaolinite and halloysite derived from sequential transformation of pedogenic smectite and kaolinite-smectite in a 120 ka tropical soil chronosequence. Clay Clay Miner. 64, 639–667. https://doi.org/10.1346/CCMN.2016.064030.

Ryan, P.C., Huertas, F.J., 2009. The temporal evolution of pedogenic Fe–smectite to Fe–kaolin via interstratified kaolin–smectite in a moist tropical soil chronosequence. Geoderma 151, 1–15. https://doi.org/10.1016/j.geoderma.2009.03.010.

Santana, D.P., 1984. Soil formation in a toposequence of Oxisols from Patos de Minas region, Minas Gerais State, Brazil. Purdue University, USA, p. 129p. PhD thesis.

Sanz-Scovino, J.I., Weil, S., Jones, A.A., 1992. The mineralogy and potassium reserves of a soil from Carimagua, Colombia. Geoderma 52, 291–302. https://doi.org/10.1016/0016-7061(92)90043-7.

Schaefer, C.E.G.R., 2001. Brazilian latosols and their B horizon microstructure as long-term biotic constructs. Austr. J. Soil Research 39, 909–926. https://doi.org/10.1071/SR00093.

Schaefer, C.E.G.R., Delrymple, J., 1995. Landscape evolution in Roraima, North Amazonia - Plantation, paleosols and paleoclimates. Z. Geomorphol. 39, 1–28.

Schaefer, C.E.G.R., Fabris, J.D., Ker, J.C., 2008. Minerals in the clay fraction of Brazilian latosols (Oxisols): a review. Clay Miner. 43, 1–18. https://doi.org/10.1180/claymin.2008.043.1.11.

Scholten, T., Felix-Henningsen, P., Schotte, M., 1997. Geology, soils and saprolites of the Swaziland Middleveld. Soil Technol. 11, 229–246. https://doi.org/10.1016/S0933-3630(97)00010-X.

Shi, X.Z., Yu, D.S., Warner, E.D., Pan, X.Z., Petersen, G.W., Gong, Z.G., Weindorf, D.C., 2004. Soil database of 1:1,000,000 digital soil survey and reference system of the Chinese Genetic Soil Classification system. Soil Surv. Horiz. 45, 129–136.

Shi, X.Z., Yu, D.S., Yang, G.X., Wang, H.J., Sun, W.X., Du, G.H., Gong, Z.T., 2006. Cross-reference benchmarks for translating the Genetic Soil Classification of China into the Chinese Soil Taxonomy. Pedosphere 16, 147–153. https://doi.org/10.1016/S1002-0160(06)60037-4.

Silva, I.R., Neto, A.E.F., Fernandes, L.A., Curi, N., Vale, F.R., 2000. Formas, relação quantidade/intensidade e biodisponibilidade de potássio em differentes Latossolos. Pesq. Agropec. Bras. Brasilia 35, 2065–2073.

Silva, L.A.D., Ker, J.C., Camelo, D.D., Fontes, M.P.F., Correa, M.M., Silva, D.L.D., 2024. Pedogenesis of pelitic rocks of the Serra da Saudade Formation - Bambuí Group. Rev. Bras. Cienc. Solo 48, e0230088. https://doi.org/10.36783/18069657rbcs20230088.

Soares, M.R., Alleoni, L.R.F., Vidal-Torrado, P., Cooper, M., 2005. Mineralogy and ion exchange properties of the particle size fractions of some Brazilian soils in tropical humid areas. Geoderma 125, 355–367. https://doi.org/10.1016/j.geoderma.2004.09.008.

Soil Survey Staff, 1975. Soil Taxonomy. A basic System of Soil Classification for making and interpreting Soil Survey. USDA, Washington D.C., Agricultural Handbook, 436p.

Soil Survey Staff, 1998. Key to Soil Taxonomy, 8th edition. Natural Resources Conservation Service, USDA, Washington DC, USA, p. 326.

Soil Survey Staff, 1999. Soil Taxonomy. A basic system of soil classification for making and interpreting soil surveys, 2nd edition. Agricultural Handbook 436, Natural Resources Conservation Service, USDA, Washington DC, USA, pp. 869.

Soil Survey Staff, 2006. Keys to Soil Taxonomy. 8 ed. United States Department of Agriculture, Natural Resources Conservation Service, Washington. Sparks, D. L, 2003. Environmental Soil Chemistry. Academic Press, London.

Steiner, F., Lana, M.C., 2018. Contribution of non-exchangeable K in soils from Southern Brazil under potassium fertilization and successive cropping. Revista Ciência Agronomica 49, 547–557. https://doi.org/10.5935/1806-6690.20180062.

Tardy, Y., Garrels, R.M., 1974. A method for estimating the Gibbs energies of formation of layer silicates. Geochim. Cosmochim. Acta 38, 1101–1116.

Testoni, S., Almeida, J.A., Silva, L., Andrade, G.R.P., 2017. Clay Mineralogy of Brazilian Oxisols with Shrinkage Properties. Rev. Bras. Ciênc. Solo 41, e016487. https://doi.org/10.1590/18069657rbcs20160487.

Tiessen, H., Hauffe, H.-H., Mermut, A.R., 1991. Deposition of Harmattan dust and its influence on base saturation of soils in northern Ghana. Geoderma 49, 285–299. https://doi-org.insu.bib.cnrs.fr/10.1016/0016-7061(91)90055-X.

de Tombeur, F., Turner, B.L., Laliberté, E., Lambers, H., Mahy, G., Faucon, M.-P., Zemunik, G., Cornelis, J.T., 2020. Plants sustain the terrestrial silicon cycle during ecosystem retrogression. Science 369, 1245–1248. https://doi.org/10.1126/science.abc0393.

Van Ranst, E., Doube, M., Mees, F., Dumon, M., Ye, L., Delvaux, B., 2019. Andosolization of ferrallitic soils in the Bambouto Mountains, West Cameroon. Geoderma 375, 81–93. https://doi.org/10.1016/j.geoderma.2018.12.024.

Van Ranst, E., Kips, P., Mbogoni, J., Mees, F., Dumon, M., Delvaux, B., 2020. Halloysite-smectite mixed-layered clay in fluvio-volcanic soils at the southern foot of Mount Kilimanjaro. Tanzania. Geoderma 375, 114527. https://doi.org/10.1016/j.geoderma.2020.114527.

Van Wambeke, A., 1992. Soils of the tropics, properties and appraisal. McGraw-Hill Inc, New York.

Van Wambeke, A., Eswaran, H., Herbillon, A., Comerma, J., 1983. Oxisols. Developments in Soil Science, Part b, Elsevier 11, 325–354. https://doi.org/10.1016/S0166-2481(08)70620-2.

Velde, B., Meunier, A., 2008. The Origin of clay minerals in soils and weathered rocks. Springer-Verlag, Berlin Heidelberg, p. 406p.

Vidal-Torrado, P., Lepsch, I.F., 1999. Soil/parent material relations and pedogenesis on a slope dominated by clayey oxidic soils over sandstone at the S. Paulo State Peripheral Depression, southeastern Brazil. R. Bras. Ciênc. Solo. 23, 357–369. https://doi.org/10.1590/S0100-06831999000200019.

Vidal-Torrado, P., Lepsch, I.F., Castro, S.S., Cooper, M., 1999. Pedogenesis of an oxisol-ultisol-alfisol sequence on the border of a plateau at the paulista peripherical depression in Brazil. R. Bras. Ciênc. Solo 23, 909–921. https://doi.org/10.1590/S0100-06831999000400018.

Volf, M.R., Benites, V.C., Azevedo, A., Moraes, M., Tiritan, C.S., Rosolem, C.A., 2023. Soil mineralogy and K reserves in soils from the Araguaia River valley. Brazil. Geoderma Regional 33, e654.

Weaver, R.M., 1974. Soils of the Central Plateau of Brazil: chemical and mineralogical properties. Agronomy, Cornell University, Ithaca, New York, Dept, p. 46p.

Zech, W., Schad, P., Hintermaier-Erhard, G., 2022. Tropics with Summer rain. In: Soils of the World. Springer, Berlin, Heidelberg. https://doi.org/10.1007/978-3-540-30461-6_9.

Zhang, M., Wilson, M.J., He, Z., 2004. Mineralogy of red soils in Southern China in relation to their development and charge characteristics. In: Wilson, M.J., He, Z., Yang, X. (Eds.), The Red Soils of China. Kluwer Academic Publishers, Dordrecht, pp. 35–61.

Zhang, H.-Z., Yang, J.-L., Sun, Y.-Q., Song, X.-D., Zhang, G.-L., 2026. Terrestrial biogeochemical silicon cycle in tropical regions: a review. Pedosphere, in Press. https://doi.org/10.1016/j.pedosph.2025.06.009.

Zörb, C., Senbayram, M., Peiter, E., 2014. Potassium in agriculture – Status and perspectives. J. Plant Physiology 171, 656–669. https://doi.org/10.1016/j.jplph.2013.08.008.