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Pedogenic Differentiation Across Volcanic Landforms in Tropical Rainforest: Evidence from Clay Activity and Carbon Dynamics in East Kalimantan, Indonesia

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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Abstract

Volcanic soils in humid tropical environments undergo intensive weathering and pedogenic differentiation, producing marked variation in clay activity and soil organic carbon across landforms. This study evaluated pedogenic differentiation across volcanic landforms in Barong Tongkok, East Kalimantan, Indonesia, using clay activity and carbon dynamics as indicators of soil development. Four representative soil profiles from the extinct volcano, volcanic shield, and lava field geomorphic units were selected for pedogenic evaluation. Morphological and physicochemical properties across genetic horizons were evaluated to assess soil development. Physicochemical data from each genetic horizon were evaluated for particle-size distribution, organic carbon, cation exchange capacity of clay, base saturation, and bulk density. Clay content generally increased with depth and was greater in the more stable landforms, exceeding 80% in several subsurface horizons of the volcanic shield and lava field profiles. Soil organic carbon was concentrated in surface horizons and declined markedly with depth, with surface values ranging from 5.07% to 10.38% across the four profiles. Subsurface clay activity was generally low to moderate, while base saturation showed substantial depletion in the more strongly weathered profiles. These vertical and spatial patterns indicate progressive mineral

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weathering, clay accumulation, and carbon differentiation across the volcanic toposequence. Overall, the results support the use of clay activity, soil organic carbon distribution, and base saturation as complementary indicators of pedogenic differentiation in humid tropical volcanic landscapes.

Keywords: Base saturation; geomorphic stability; soil evolution; soil weathering; toposequence.

1. Introduction

Volcanic soils represent some of the most dynamic pedogenic systems due to their highly reactive parent materials and rapid mineral weathering under humid tropical conditions. These soils undergo intensive chemical alteration, resulting in the formation of secondary clay minerals and pedogenic oxides that strongly influence soil physicochemical properties and ecosystem functioning (Buol et al., 2011; Dahlgren et al., 2004; Hartemink & Bockheim, 2013; Wilson et al., 2017). In tropical environments, prolonged weathering promotes desilication and transformation of primary volcanic minerals into kaolinite and iron-aluminium oxides, which represent advanced stages of soil development (Anda & Dahlgren, 2020). These mineral transformations regulate nutrient retention, soil structure, and carbon stabilisation, making volcanic soils critical components of global biogeochemical cycles (Lehmann et al., 2020; Wiesmeier et al., 2019).

Clay mineral evolution represents a key mechanism controlling pedogenic differentiation and soil maturity in tropical volcanic landscapes. As pedogenesis progresses, clay mineral assemblages shift from high-activity minerals such as smectite and allophane towards low-activity minerals such as kaolinite and sesquioxides, resulting in decreased cation exchange capacity and nutrient availability (Bünemann et al., 2018; Buol et al., 2011; Hartemink & Bockheim, 2013). Clay activity, expressed as cation exchange capacity per unit clay, provides a reliable indicator of mineral weathering intensity and soil evolutionary status (Soil Survey Staff, 2022). This progressive decline in clay activity reflects prolonged weathering, mineral transformation, and pedogenic differentiation under stable tropical conditions (Beckford et al., 2023). Recent evidence from a volcanic soil chronosequence indicates that pedogenic mineralogical changes from short-range-order phases through more active clays to low-activity clays can coincide with changes in organic-carbon stabilisation (Chittamart et al., 2024).

Topographic position plays a fundamental role in regulating pedogenesis by controlling erosion intensity, drainage conditions, and soil residence time. Along volcanic toposequences, soils typically evolve from weakly developed profiles on unstable upper slopes to highly weathered soils at stable lower positions (Schaetzl & Thompson, 2015). Stable geomorphic surfaces allow prolonged weathering and clay accumulation, whereas unstable positions experience erosion that limits soil development (Phillips, 2017). These landscape-controlled variations create systematic gradients in clay content, mineral composition, and soil classification across volcanic terrains (Beckford et al., 2023).

Soil organic carbon dynamics are closely linked to pedogenic processes and mineralogical evolution in volcanic soils. Carbon stabilisation in tropical soils is primarily controlled by interactions between organic matter and mineral surfaces, particularly clay minerals and pedogenic oxides (Lehmann et al., 2020; Wiesmeier et al., 2019). However, advanced weathering often reduces carbon retention capacity due to the dominance of low-activity clay minerals with limited adsorption capacity (Reichenbach et al., 2021). Conversely, amorphous aluminium and iron phases formed during early weathering stages can enhance carbon stabilisation through organo-mineral associations (Takahashi & Dahlgren, 2016). These interactions highlight the importance of mineralogical evolution in controlling carbon dynamics during pedogenesis.

Experimental evidence also indicates that clay mineralogy and sesquioxide abundance can influence soil organic carbon stabilisation, underscoring the relevance of mineralogical composition when interpreting carbon dynamics (Das et al., 2024). Recent field observations have likewise documented a decrease in soil organic carbon with depth across contrasting land-use and elevational settings, supporting the interpretation of vertical SOC differentiation as context-dependent (Tarafder et al., 2025). A recent depth-resolved assessment further reported that organic carbon varied with soil depth and texture, with stronger accumulation near the surface, reinforcing the relevance of texture and profile position to carbon distribution (Yadav & Ram, 2025).

Despite the importance of volcanic soils in tropical ecosystems, an integrated evaluation of clay activity and carbon dynamics across volcanic landforms remains limited, particularly in Southeast Asia. Previous studies have primarily focused on soil classification or mineralogical properties, without fully examining their relationships with carbon stabilisation and pedogenic differentiation (Anda & Dahlgren, 2020). In Indonesia, volcanic landscapes have experienced prolonged tropical weathering, providing ideal conditions to study advanced pedogenesis and soil evolution. Therefore, this study aims to evaluate pedogenic differentiation across volcanic landforms in East Kalimantan, Indonesia, using clay activity and carbon dynamics as indicators of soil development. This study provides new insights into pedogenic processes and contributes to an improved understanding of soil evolution in humid tropical volcanic environments. Accordingly, the objective of this study is to evaluate pedogenic differentiation across volcanic landforms in East Kalimantan, Indonesia, using clay activity and carbon dynamics as indicators of soil development.

2. Material and Methods

2.1 Study Area

The study was conducted in the volcanic landscape of Barong Tongkok and surrounding areas, East Kalimantan Province, Indonesia, located between approximately 115°38′–115°44′ E longitude and 0°10′–0°16′ S latitude (Fig. 1). The area is situated in the equatorial region and is dominated by tropical rainforest ecosystems developed on volcanic landforms, including extinct volcanic slopes, volcanic shields, and lava fields. These volcanic landforms provide diverse parent materials and landscape positions that strongly influence soil formation and pedogenic processes. Variations in geomorphic position and volcanic material contribute to differences in soil morphological and physicochemical characteristics across the landscape (Buol et al., 2011; Dahlgren et al., 2004; Hartemink & Bockheim, 2013).

Climatically, the study area is characterised by a humid tropical rainforest climate with high rainfall and uniformly warm temperatures throughout the year. According to the Indonesian Agency for Meteorology, Climatology, and Geophysics, East Kalimantan receives annual rainfall exceeding 2000 mm, with mean annual temperatures ranging from 26 to 27 °C (Badan Meteorologi, Klimatologi, dan Geofisika, n.d.). These climatic conditions promote intensive chemical weathering, clay mineral formation, and organic matter accumulation, which accelerate soil development in tropical volcanic environments (Aldrian & Dwi Susanto, 2003; Nugroho et al., 2026; Quesada et al., 2011). Such environmental conditions provide a suitable setting to evaluate pedogenic differentiation across volcanic landforms.

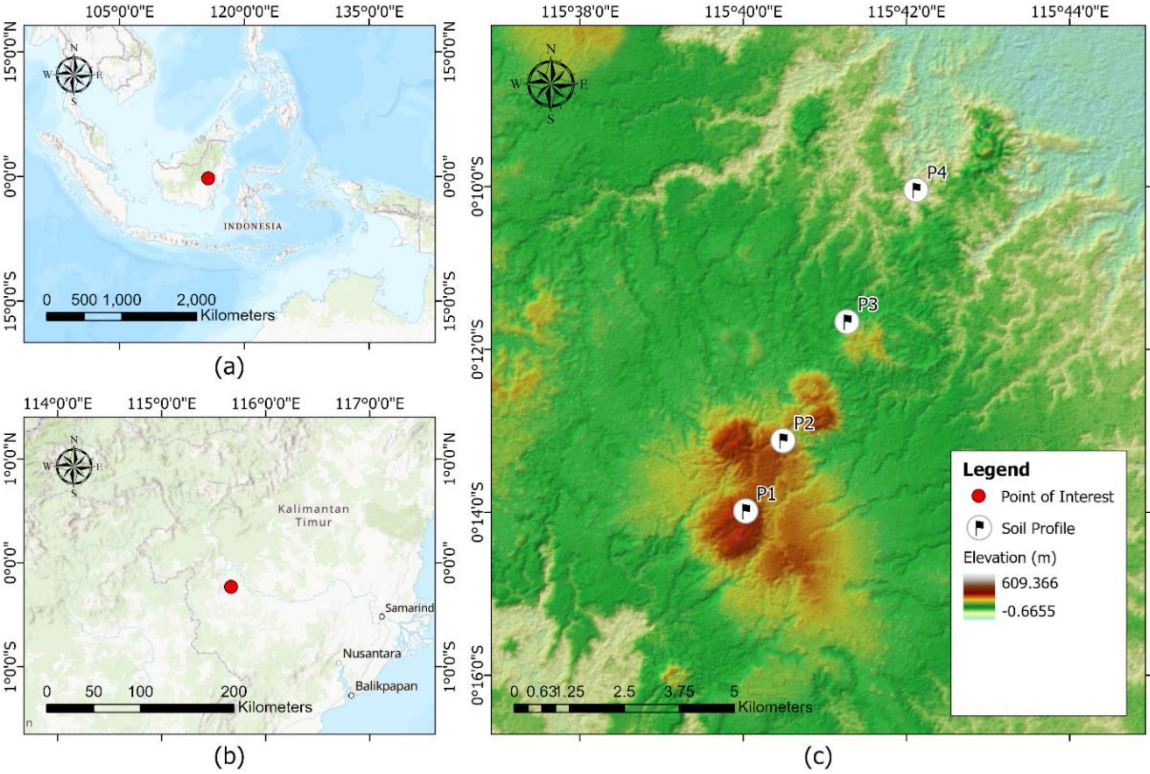

Fig. 1. Location of the study area and approximate spatial representation of the selected soil profiles across volcanic landforms in the Barong Tongkok area, East Kalimantan, Indonesia. The positions of P1–P4 in panel (c) represent their respective geomorphic settings and are not intended to indicate the exact coordinates of the original soil profiles

2.2 Soil Sampling and Profile Description

Four representative soil profiles were selected from the soil investigation dataset for pedogenic evaluation, representing the extinct volcano upper slope (P1), extinct volcano lower slope (P2), volcanic shield (P3), and lava field (P4). The Barong Tongkok area is characterized by three major volcanic geomorphic units, namely the lava field, volcanic shield, and extinct volcano (Aksa et al., 2000). The profiles were located on the extinct volcano upper slope (P1), the extinct volcano lower slope (P2), the volcanic shield (P3), and the lava field (P4), forming a volcanic toposequence. The toposequence approach is widely applied in pedological studies to evaluate soil variability and pedogenic processes along landscape gradients, as soil properties are strongly influenced by slope position, elevation, and parent material distribution (Alves et al., 2024).

Morphological characteristics for each genetic horizon, including horizon designation, depth, soil colour, and texture, were compiled from the earlier soil investigation and are presented in Table 1. Pedon morphological characteristics were adapted from Aksa et al. (2000). A soil profile represents a vertical section of soil divided into genetic horizons, and its description forms the basis for understanding soil formation, classification, and functional interpretation (Hartemink et al., 2020; Hartemink & Minasny, 2014). Soil colour was determined under moist conditions using the Munsell Soil Color Chart, while soil texture was assessed in the field and verified by laboratory particle size analysis. Standard soil survey procedures were followed to ensure accurate characterisation and comparability of soil morphological properties across profiles (Soil Science Division Staff, 2017).

Physicochemical data corresponding to the selected genetic horizons were used to evaluate pedogenic differentiation across the volcanic landforms. Evaluation based on genetic horizons is important for assessing pedogenic differentiation because soil properties vary systematically with depth due to weathering, clay translocation, and organic matter accumulation (Wilson et al., 2017). These data were subsequently evaluated to determine vertical patterns in soil physicochemical properties and to interpret soil development across volcanic landforms.

Table 1. Morphological characteristics of soil profiles across volcanic landforms in Barong Tongkok, East Kalimantan, Indonesia

Profile	Landform	Horizon	Depth (cm)	Colour (moist)	Texture
P1	Extinct volcano upper slope	AE	0–8	7.5YR 3/3	Clay
		BE	8–26	7.5YR 3/3	Clay
		Bt1	26–52	7.5YR 3/4	Clay
		Bt2	52–80	7.5YR 3/4	Clay
		B3	80–115	5YR 3/4	Clay
		CD	115–160	5YR 3/6	Loam
P2	Extinct volcano lower slope	Ah	0–10	10YR 2/3	Clay
		B1	10–46	10YR 2/3	Clay
		B2	46–70	10YR 4/3	Clay
		B3	70–96	10YR 4/4	Clay
		B4	96–160	10YR 4/5	Clay
		B5	160–200	10YR 4/6	Clay
P3	Volcanic shield	Ah	1–20	2.5YR 2/4	Clay
		Bt1	20–49	2.5YR 3/4	Clay
		Bt2	49–78	2.5YR 3/4	Clay
		Bt3	78–110	2.5YR 3/4	Clay
		Bt4	110–154	2.5YR 3/5	Clay
		BC	154–200	2.5YR 3/6	Clay
P4	Lava field	Ah	0–10	7.5YR 2/3	Clay loam
		B1	10–32	10YR 2/3	Clay
		B2	32–67	10YR 3/3	Clay
		B3	67–100	10YR 3/3	Clay
		B4	100–148	10YR 3/3	Clay
		B5	148–200	10YR 3/3	Clay

Source: Adapted from Aksa et al. (2000)

2.3 Physicochemical Data

Physicochemical data for the selected soil profiles were compiled from the soil investigation reported by Aksa et al. (2000). The variables used in the present study included particle-size distribution (sand, silt, and clay fractions), soil organic carbon (SOC), cation exchange capacity of clay (CEC clay), base saturation (BS), and bulk density (BD). These properties were selected to evaluate vertical differentiation and pedogenic development across the volcanic landforms. Particle-size distribution was evaluated to assess textural differentiation and clay accumulation across genetic horizons. Clay content provides an important indicator of soil weathering and horizon differentiation, particularly in volcanic soils where mineral transformation and clay formation are major pedogenic processes (Dahlgren et al., 2004). Soil texture also provides information on soil physical behaviour, nutrient retention, and water-holding capacity (Soil Science Division Staff, 2017).

Soil organic carbon was evaluated to characterise the vertical distribution of organic matter within the profiles. Organic carbon is an important indicator of soil development and is closely associated with aggregate stability, nutrient cycling, and cation exchange processes (Lal, 2020; Ma et al., 2019). Its distribution within soil profiles reflects interactions among vegetation inputs, decomposition, mineral surfaces, and pedogenic processes (Quesada et al., 2011).

CEC clay and base saturation were used as indicators of clay activity and chemical weathering, respectively. CEC clay reflects the charge characteristics and reactivity of the clay fraction, whereas base saturation provides an indication of base-cation depletion associated with weathering and leaching (Hazelton & Murphy, 2016; Weil & Brady, 2016). Bulk density was included as an indicator of soil physical condition and profile development (Blake & Hartge, 1986). The compiled physicochemical data were subsequently evaluated for vertical patterns and differences among volcanic landforms.

2.4 Data Analysis

Data were analysed descriptively to evaluate pedogenic trends across landforms. The physicochemical properties of the soil, including clay content, organic carbon, cation exchange capacity of clay, base saturation, and bulk density, were analysed to evaluate their vertical distribution and variation across different volcanic landforms. Vertical distribution patterns were examined based on genetic horizons to identify pedogenic processes such as clay accumulation, organic matter enrichment, and weathering intensity. Vertical differentiation of soil properties is commonly used to interpret soil development and horizon formation, particularly in volcanic landscapes where pedogenesis is strongly influenced by parent material and environmental conditions (Dahlgren et al., 2004; Schaetzl & Thompson, 2015).

Comparative analysis of soil profiles was conducted to assess the influence of volcanic landforms on soil development. Differences in soil properties between profiles were interpreted in relation to landscape position and geomorphic setting. The toposequence approach provides an effective framework for evaluating spatial variability of soil properties and understanding the relationship between landforms and pedogenic processes (Jenny, 1994; Wilson et al., 2017). Variations in clay content and organic carbon were used as key indicators of soil weathering and development intensity.

Clay activity was evaluated using cation exchange capacity of clay, which reflects the mineralogical characteristics and reactivity of soil colloids. The relationship between clay content and CEC clay provides insight into soil fertility and the degree of weathering, particularly in highly weathered tropical soils (Weil & Brady, 2016; Hazelton & Murphy, 2016). Bulk density values were interpreted to assess soil physical condition and structural development, as lower bulk density generally indicates higher porosity and better soil structure (Blake & Hartge, 1986).

Descriptive statistics, including mean values and vertical trends were used to evaluate pedogenic differentiation across landforms. Comparative interpretation of soil profiles was conducted to identify systematic variations associated with geomorphic position. All descriptive statistical analyses were performed using Microsoft Excel (Microsoft Corporation, Redmond, WA, USA). These analyses were used to calculate mean values, evaluate vertical trends, and compare pedogenic indicators among volcanic landforms.

3. Results and Discussion

3.1 Results

Clay content showed clear vertical variation within each soil profile and systematic differences across volcanic landforms in the Barong Tongkok landscape (Table 2; Fig.2). In general, clay content increased with depth in most profiles, indicating progressive pedogenic development and clay translocation. This trend reflects the influence of weathering intensity and geomorphic stability on soil formation processes, particularly in humid tropical volcanic environments where clay formation is a dominant pedogenic mechanism.

In the extinct volcano upper slope profile (P1), clay content increased gradually from 51.5% in the surface horizon to a maximum of 59.5% in the subsurface horizon before decreasing sharply in the parent material layer (Table 2). The moderate clay accumulation and absence of extremely high clay content suggest relatively weak pedogenic development under erosional and well-drained conditions. Limited clay enrichment in subsurface horizons indicates restricted clay illuviation, which is consistent with unstable geomorphic conditions commonly observed at upper slope positions.

Table 2. Physical and chemical properties of soil profiles across volcanic landforms in Barong Tongkok

Profile	Landform	Hor.	Depth (cm)	Sand (%)	Silt (%)	Clay (%)	Organic C (%)	CEC clay (cmol(+).kg-1)	Base Sat. (%)	Bulk Den. (g.cm-3)
P1	Extinct volcano upper slope	AE	0–8	37.0	11.5	51.5	6.35	14.7	68.0	0.45
		BE	8–26	31.5	13.2	55.3	3.24	16.0	42.4	0.68
		Bt1	26–52	30.1	10.4	59.5	1.71	7.4	35.2	0.75
		Bt2	52–80	28.4	14.1	57.5	0.81	11.0	40.1	0.77
		B3	80–115	33.2	20.8	46.0	0.78	9.5	59.8	0.77
		CD	115–160	63.2	26.2	10.6	0.52	11.9	32.8	0.72
P2	Extinct volcano lower slope	Ah	0–10	22.7	11.1	66.2	8.49	14.7	53.9	0.57
		B1	10–46	17.0	13.4	69.6	2.48	16.0	30.8	0.62
		B2	46–70	11.8	9.8	78.4	1.67	7.4	16.1	0.69
		B3	70–96	12.8	9.7	77.5	1.15	11.0	13.9	0.73
		B4	96–160	11.8	7.8	80.4	0.82	9.5	8.1	0.86
		B5	160–200	9.9	6.6	83.5	0.55	11.9	11.0	0.93
P3	Volcanic shield	Ah	1–20	25.4	18.4	55.7	5.07	14.7	55.6	0.57
		Bt1	20–49	7.4	17.3	75.3	2.09	16.0	22.4	0.71
		Bt2	49–78	10.6	8.5	80.9	1.43	7.4	16.3	0.69
		Bt3	78–110	8.3	9.0	82.7	0.83	11.0	19.1	0.79
		Bt4	110–154	9.6	8.8	81.6	0.62	9.5	16.6	0.79
		BC	154–200	9.0	8.3	82.7	0.44	11.9	16.6	0.78
P4	Lava field	Ah	0–10	32.3	27.6	40.1	10.38	53.9	21.0	0.47
		B1	10–32	14.2	14.7	71.1	3.57	15.6	31.6	0.58
		B2	32–67	13.3	13.2	73.5	1.73	21.0	54.2	0.67
		B3	67–100	8.5	10.3	81.2	0.85	11.1	49.0	0.72
		B4	100–148	8.5	10.4	80.9	0.68	17.8	55.4	0.82
		B5	148–200	10.5	8.7	80.8	0.56	10.7	65.6	0.87

Source: Adapted from Aksa et al. (2000)

In contrast, soils developed on the extinct volcano lower slope (P2) exhibited a more pronounced increase in clay content with depth, reaching values as high as 83.5% in deeper horizons. This substantial clay accumulation reflects enhanced weathering intensity and prolonged soil residence time compared to the upper slope position. The gradual increase in clay content indicates active pedogenic processes, including mineral transformation and clay neoformation, under relatively stable geomorphic conditions. Soils formed on volcanic shield landforms (P3) showed consistently high clay content throughout the profile, with subsurface horizons exceeding 80% clay. These high clay values indicate advanced pedogenic development and intensive weathering of volcanic parent materials. Strong clay accumulation and uniform distribution across horizons suggest prolonged pedogenic stability and continuous mineral transformation.

The lava field profile (P4) exhibited the most advanced clay enrichment among all profiles. Clay content increased sharply from 40.1% in the surface horizon to more than 80% in subsurface horizons. Such high clay accumulation reflects intensive weathering and prolonged pedogenic processes under stable landscape conditions. These results demonstrate a clear pedogenic gradient across volcanic landforms, where clay accumulation increased from upper slope to lava field positions, indicating progressive soil development associated with geomorphic stability.

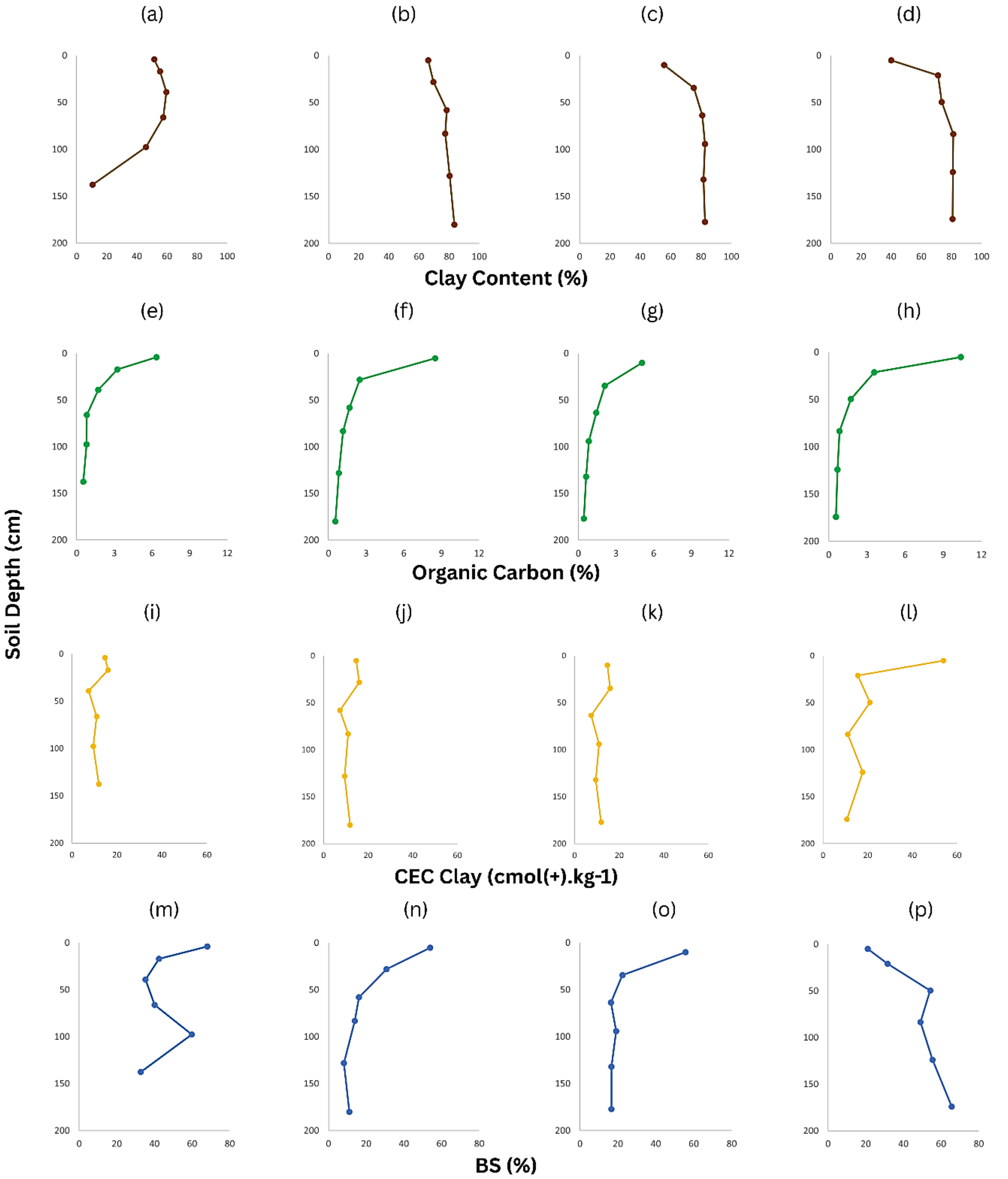

Fig. 2. Vertical distribution of clay content, soil organic carbon, clay cation exchange capacity (CEC clay), and base saturation (BS) across volcanic landforms in the Barong Tongkok volcanic landscape, East Kalimantan, Indonesia

Organic carbon content showed strong vertical differentiation within soil profiles and distinct variation across volcanic landforms, reflecting differences in pedogenic development and landscape stability (Table 2; Fig. 2). In general, organic carbon concentrations were highest in surface horizons and decreased sharply with depth in all profiles. This pattern reflects the dominant influence of vegetation inputs at the surface and limited downward transport of organic matter in highly weathered tropical soils.

The extinct volcano upper slope profile (P1) showed relatively high organic carbon content in the surface horizon (6.35%), followed by a rapid decline to less than 1% in deeper horizons. This sharp decrease indicates limited stabilisation of organic carbon in subsurface horizons, which is consistent with active erosion, rapid drainage, and reduced pedogenic stability at upper slope positions. Such conditions restrict the accumulation and preservation of organic carbon within deeper soil layers.

In contrast, the extinct volcano lower slope profile (P2) exhibited higher organic carbon content in the surface horizon (8.49%), followed by a gradual decrease with depth. The higher surface organic carbon content compared with that of the upper-slope profile suggests greater biomass input and improved stabilisation under more stable geomorphic conditions. However, subsurface horizons still showed relatively low organic carbon levels, indicating limited vertical translocation and strong mineralisation under tropical climatic conditions.

Soils developed on the volcanic shield (P3) showed moderate organic carbon content in the surface horizon (5.07%), with a gradual decline in deeper horizons. The relatively stable organic carbon distribution reflects improved soil structural stability and enhanced interactions between organic matter and clay minerals. High clay content in subsurface horizons promotes organo-mineral associations, which enhance organic carbon stabilisation and persistence in tropical soils.

The lava field profile (P4) exhibited the highest organic carbon content among all profiles, reaching 10.38% in the surface horizon. This exceptionally high organic carbon content reflects strong organic matter accumulation and effective stabilisation under highly weathered and clay-rich soil conditions. The combination of high clay content and low bulk density promotes the formation of stable soil aggregates, which protect organic carbon from decomposition. These results demonstrate that organic carbon dynamics are strongly controlled by volcanic landforms, with greater organic carbon accumulation and stabilisation occurring under more stable geomorphic conditions.

Organic carbon distribution across volcanic landforms reflects a clear pedogenic gradient associated with landscape stability and clay accumulation. Higher organic carbon content in volcanic shield and lava field soils indicates stronger pedogenic development and enhanced organo-mineral interactions. This relationship highlights the important role of clay content and soil development in controlling carbon dynamics in tropical volcanic landscapes.

Clay activity, as indicated by cation exchange capacity of clay (CEC clay), showed clear variation within and among soil profiles, reflecting differences in mineral weathering intensity and pedogenic development across volcanic landforms (Table 2; Fig. 2). In general, CEC clay values ranged from moderate to low across most subsurface horizons, indicating the dominance of low-activity clay minerals associated with advanced weathering in tropical environments.

In the extinct volcano upper slope profile (P1), CEC clay values ranged from 7.4 to 16.0 cmol(+).kg-1 in subsurface horizons. These moderate values suggest the presence of mixed clay mineral assemblages, including both relatively active and weathered minerals. The variability in CEC clay within the profile reflects moderate pedogenic development and incomplete mineral transformation under erosional and unstable geomorphic conditions. The relatively higher base saturation and lower clay accumulation further indicate limited weathering intensity compared to more stable landforms.

The extinct volcano lower slope profile (P2) exhibited generally lower CEC clay values, particularly in deeper horizons where values decreased to 7.4 cmol(+).kg-1. These low values indicate advanced mineral weathering and the dominance of low-activity clay minerals such as kaolinite and iron–aluminium oxides. The progressive decline in CEC clay with depth suggests increasing pedogenic intensity and prolonged mineral transformation under relatively stable landscape conditions.

Soils developed on the volcanic shield (P3) showed consistently low CEC clay values despite very high clay content. This combination of high clay percentage and low CEC clay clearly indicates the dominance of highly weathered, low-activity clay minerals. These characteristics reflect advanced pedogenic development associated with prolonged weathering, intensive leaching, and stable geomorphic conditions. The low activity of clay minerals also suggests extensive desilication and accumulation of secondary minerals typical of tropical weathering environments.

The lava field profile (P4) exhibited a similar pattern of generally low to moderate CEC clay values, despite extremely high clay content in subsurface horizons. The presence of low-activity clay minerals combined with high clay accumulation indicates advanced pedogenic development and strong mineral transformation. However, slightly higher CEC clay values in some horizons may reflect minor contributions from less weathered mineral components or organic matter interactions.

Clay activity decreased with increasing pedogenic development across volcanic landforms. The transition from moderate clay activity in upper slope soils to low clay activity in volcanic shield and lava field soils reflects progressive mineral weathering and soil evolution. These results confirm that clay activity provides clear evidence of pedogenic differentiation and serves as a reliable indicator of soil development intensity in tropical volcanic landscapes.

Base saturation (BS) showed pronounced variation with depth and across volcanic landforms, reflecting differences in leaching intensity and degree of soil weathering (Table 2; Fig. 2). In general, base saturation decreased with increasing pedogenic development, indicating progressive depletion of exchangeable base cations under humid tropical conditions. This trend is consistent with intensive chemical weathering and leaching commonly observed in highly weathered tropical soils.

In the extinct volcano upper slope profile (P1), base saturation values were relatively high in the surface horizon (68.0%) and remained moderate in subsurface horizons, ranging from 32.8% to 59.8%. These relatively high values indicate limited leaching and less advanced weathering compared with other profiles. The higher base status suggests a shorter soil residence time and reduced pedogenic intensity, which is consistent with the unstable geomorphic conditions at upper-slope positions where erosion limits soil development.

In contrast, the extinct volcano lower slope profile (P2) showed a marked decrease in base saturation with depth, reaching values as low as 8.1% in deeper horizons. This substantial reduction reflects intensive leaching of base cations and advanced chemical weathering under more stable landscape conditions. The low base saturation indicates strong depletion of weatherable minerals and accumulation of secondary clay minerals, which are typical features of highly weathered tropical soils.

Soils developed on the volcanic shield (P3) exhibited consistently low base saturation values throughout the profile, generally ranging between 16% and 22% in subsurface horizons. These low values reflect prolonged leaching and advanced pedogenic development. The combination of high clay content, low clay activity, and low base saturation clearly indicates intensive mineral weathering and the dominance of highly weathered clay mineral assemblages.

The lava field profile (P4) exhibited variable base saturation values, with relatively low values in surface horizons and moderate values in deeper horizons. Despite this variability, the overall pattern reflects advanced weathering conditions associated with prolonged pedogenic development and clay accumulation. The relatively moderate base saturation in some deeper horizons may reflect inherited characteristics from parent materials or localised variations in leaching intensity.

Base saturation showed a clear relationship with pedogenic development across volcanic landforms. Lower base saturation in volcanic shield and lava field soils reflects more advanced weathering and prolonged leaching compared with upper-slope soils. These findings confirm that base saturation is a reliable indicator of weathering intensity and supports the interpretation of progressive pedogenic differentiation across the Barong Tongkok volcanic landscape.

3.2 Discussion

This study demonstrated clear pedogenic differentiation across volcanic landforms, characterised by increasing clay accumulation and declining clay activity and base saturation from upper slope to stable volcanic positions. These findings indicate progressive soil weathering and mineral transformation associated with geomorphic stability in tropical volcanic environments. Surwase et al. (2023) reported systematic downslope increases in clay content and CEC from the summit to the plains in a basaltic landscape. In our profiles, we observed the same signal of progressive weathering (kaolinite-rich clays, low CEC and base saturation) at lower positions, mirroring patterns noted by others in humid tropical volcanic soils. This downslope increase in clay accumulation is primarily driven by progressive desilication and clay neoformation under stable geomorphic conditions, which promote the transformation of primary minerals into secondary low-activity clay minerals such as kaolinite and sesquioxides. These mineralogical transformations represent key pedogenic mechanisms that control soil evolution in humid tropical environments (van Breemen & Buurman, 1998; Lehmann et al., 2020).

At the same time, we note contrasting evidence in the literature that emphasises parent-material effects. Reichenbach et al. (2023) found that soil geochemical differences inherited from the parent rock could outweigh topographic controls on carbon dynamics because parent-material geochemistry affects SOC stocks and mineral-related C stabilisation mechanisms. In other words, even deeply weathered tropical soils may retain a memory of their rock chemistry, influencing clay mineralogy and fertility independently of slope. Likewise, recent studies in volcanic island ecosystems highlight a complex interplay of factors – including parent material, relief, climate, and even biotic activity – in shaping soil profiles (Gerzabek et al., 2025). These findings suggest that pedogenesis cannot be attributed to topography alone. In particular, the interaction between geomorphic stability and parent material composition influences the rate of mineral dissolution, base cation depletion, and clay mineral transformation, ultimately determining the pedogenic trajectory of volcanic soils.

In summary, our results align with the view that geomorphic stability promotes progressive soil development in tropical volcanic landscapes. However, they also remind us that pedogenesis is multifactorial. Mineralogy and nutrient supply from the parent rock can modulate the weathering trajectory, and local agents (e.g., biota) may introduce additional complexity. Recognising both perspectives – slope-driven weathering and inherited lithological effects – provides a more balanced understanding of soil differentiation in these environments. Importantly, the progressive decline in clay activity and base saturation observed in this study provides clear mechanistic evidence of pedogenic differentiation. The dominance of low-activity clay minerals in lower landscape positions reflects advanced mineral weathering and prolonged soil development. These findings confirm that clay activity serves as a reliable indicator of pedogenic maturity and can be used to evaluate soil evolutionary status in tropical volcanic landscapes.

Clay activity, as measured by CEC per unit clay, is widely recognised as a robust indicator of mineral weathering. In highly weathered soils (e.g., Ultisols and Oxisols), CEC/clay values are very low because low-activity clays (kaolinite, iron oxides) predominate (Ouyang et al., 2021). In our profiles, subsurface CEC/clay values ranged from 7.4 to 16.0 cmol(+).kg-1 clay in P2 and P3 and from 10.7 to 21.0 cmol(+).kg-1 clay in P4, consistent with advanced weathering. This matches the pattern noted in upland

Asian soils: as pedogenesis increases (CEC/clay decreases), the kaolinite content increases, whereas the content of 2:1 clay minerals decreases (Gerzabek et al., 2025). In other words, intense chemical weathering produces soils rich in 1:1 clays and oxides with very low charge, driving CEC/clay downward.

By contrast, less developed or volcanically influenced soils retain high-activity minerals and higher CEC. For example, the P4 (lava-field) surface soil had exceptionally high CEC/clay (~54 cmol(+).kg-1), reflecting allophanic and smectitic components in this Andic horizon. As observed by Ouyang et al. (2021), 1:1 clays dominate in strongly weathered Ultisols/Oxisols (low CEC), whereas 2:1 clays (e.g., smectite) occur in younger, weakly weathered soils (high CEC). In our classification, surface soils on steep slopes (Inceptisols) contain more active clays and correspondingly higher CEC/clay, while deep Bs horizons on stable slopes (Kandic/Argillic horizons) are dominated by low-activity clays and very low CEC/clay.

Overall, the CEC/clay patterns in our toposequence reinforce its value as a pedogenic maturity gauge. Soils with strongly leached, low-activity clays (low CEC/clay) indicate advanced weathering, whereas soils preserving active clays (high CEC/clay) suggest younger or more volcanically influenced development. We note that parent material can modulate these trends: soils derived from basalt or volcanic ash may retain higher CEC due to persistent smectite or allophane. Nonetheless, the clear decline in clay activity from upland to lowland soils in our study is consistent with the literature's view that CEC/clay is a reliable proxy for soil evolution in tropical landscapes. The observed decrease in clay activity along the toposequence reflects progressive mineral transformation and advanced pedogenic development. This confirms that CEC per unit clay provides a robust proxy for assessing pedogenic differentiation and soil evolutionary stage in tropical volcanic environments.

Soil organic carbon dynamics in tropical volcanic landscapes are strongly controlled by mineralogical and weathering factors. Recent studies emphasise that SOC stabilisation is linked more to soil geochemistry (clay mineralogy, oxide content, weathering stage) than to slope or land use. For example, Reichenbach et al. (2023) found that carbon storage was governed more by geochemical properties (pedogenic metal phases, clay mineralogy, texture) and by the degree of soil weathering than by topography. Because our lower-slope soils are highly weathered (kaolinite- and Fe-oxide-rich), they inherently have a low capacity to bind organic matter. In other words, despite high inputs from tropical biomass, the deeply weathered Oxisol-like horizons in our profiles have reduced reactivity, which limits C storage (kaolinite and crystalline Fe/Al oxides do not sorb OC strongly).

Our data show that organic carbon is concentrated in the A horizons and declines sharply with depth. This pattern is consistent with other tropical soils, where SOC largely accumulates where fresh inputs meet relatively reactive surfaces. For instance, Anindita et al. (2023) reported that in young Indonesian volcanic Andosols, enhanced formation of amorphous Al-(hydr)oxides under agriculture promoted aggregation and physical occlusion of OC. They found strong correlations between oxalate-extractable Al and SOC in stable aggregates, and higher Al oxide content in cultivated soils was associated with greater OC occlusion and reduced SOC degradability. This suggests that pedogenic oxides (Al/Fe) can create micro-aggregate environments that protect organic C, partially compensating for the otherwise low sorption capacity of these soils.

In sum, our findings – a sharp decline of OC with depth and a strong SOC–clay association in the surface – align with the view that pedogenic development governs carbon distribution. Highly weathered soils with inert mineralogy tend to store less SOC, whereas any factors that increase reactive surface (e.g., formation of Al/Fe oxides, organic inputs) can enhance stabilisation. While topography and vegetation affect C input and distribution, the preponderance of recent literature indicates that mineralogical properties and weathering stage are the dominant controls on SOC stabilisation in tropical volcanic terrains. These results demonstrate that carbon stabilisation in these soils is closely linked to pedogenic processes and mineralogical evolution. The interaction between organic matter and weathered clay minerals plays a fundamental role in controlling carbon dynamics during soil development.

The systematic change in soil orders along our toposequence has clear implications for soil taxonomy and landscape history. Upper-slope positions produced weakly developed Inceptisols, whereas lower positions produced more intensely weathered Ultisols and Oxisols. This downslope sequence (Inceptisol to Ultisol/Oxisol) matches classic tropical catenas. For example, Anjos et al. (1998) documented that stable summits in Brazilian highlands form deeply weathered Typic Hapludox (Oxisols), while eroding slopes yield Kandic Udults and younger Inceptisols. Our profiles follow the same pattern: the most stable summit soils have Kandic/Argillic horizons (Ultisols/Oxisols), and the steep, younger landscape positions yield only cambic Inceptisols.

This pattern indicates that geomorphic stability and soil residence time govern soil classification more than parent material age. In other words, landscape position creates a pedogenic continuum in which soil order changes predictably with slope and stability. This has practical implications: soil survey and land-use planning in humid tropical regions should explicitly account for topography. The footslope soils (Ultisols/Oxisols) reflect long-term stability and strong leaching, whereas upslope soils (Inceptisols) reflect ongoing erosion and limited weathering. Recognising this gradient is essential, since areas with similar parent rocks can belong to different soil orders purely due to their position. In summary, our findings confirm that geomorphology acts as a first-order control on soil classification in old tropical landscapes, consistent with theories of landscape evolution and soil–landscape models in humid tropics.

Overall, the observed soil sequence represents a clear pedogenic continuum driven by geomorphic stability and long-term weathering. The transition from weakly developed Inceptisols to highly weathered Ultisols and Oxisols demonstrates progressive soil evolution controlled by landscape position. These findings highlight the importance of clay activity and carbon dynamics as key indicators of pedogenic differentiation in tropical volcanic landscapes.

4. Conclusion

This study demonstrated clear pedogenic differentiation across volcanic landforms in the Barong Tongkok tropical volcanic landscape, as evidenced by systematic variations in clay content, clay activity, base saturation, and soil organic carbon distribution. Clay content increased progressively from the upper slope to more stable volcanic shield and lava field positions, reflecting enhanced mineral weathering and clay neoformation under prolonged pedogenic conditions. The accumulation of high clay content in subsurface horizons, combined with the presence of argillic features, indicates advanced soil development associated with geomorphic stability and extended soil residence time.

Clay activity, expressed as cation exchange capacity per unit clay, showed a clear declining trend with increasing pedogenic development. Lower clay activity in volcanic shield and lava field soils indicates the dominance of highly weathered low-activity clay minerals such as kaolinite and iron–aluminium oxides, which represent advanced stages of mineral transformation. This confirms that clay activity provides a robust indicator of soil evolutionary status and reflects progressive mineral weathering along the volcanic toposequence.

Soil organic carbon dynamics were strongly controlled by pedogenic processes and mineralogical evolution. Organic carbon was concentrated in surface horizons and decreased sharply with depth, indicating limited stabilisation in highly weathered subsurface horizons. However, relatively high organic carbon content in stable landforms suggests enhanced organo-mineral interactions and structural stabilisation associated with high clay content and pedogenic oxide formation. These findings demonstrate that carbon dynamics in tropical volcanic soils are closely linked to pedogenic development and mineralogical transformation.

Base saturation further confirmed progressive soil weathering across volcanic landforms, with lower values observed in more developed soils. This depletion of exchangeable base cations reflects prolonged leaching and advanced chemical weathering under humid tropical conditions. The combined evidence from clay accumulation, clay activity decline, organic carbon distribution, and base saturation confirms the presence of a pedogenic continuum controlled primarily by geomorphic stability and long-term weathering.

Overall, this study highlights the critical role of clay activity and carbon dynamics as sensitive indicators of pedogenic differentiation in tropical volcanic landscapes. The results provide new insights into soil evolutionary processes in humid tropical environments and improve the understanding of how geomorphic position regulates soil development, mineral transformation, and carbon stabilisation. These findings contribute to the advancement of pedological knowledge of tropical volcanic soils and provide a scientific basis for soil classification, land evaluation, and sustainable soil management in volcanic regions.

5. Limitations

This study provides a profile-scale assessment based on four representative soil profiles and descriptive comparisons of measured physicochemical properties. Accordingly, the findings characterise the sampled volcanic toposequence but should not be interpreted as a spatially exhaustive assessment of the wider landscape. The conclusions are therefore specific to the observed profiles, horizons, and measured pedogenic indicators. Broader spatial replication would be required to evaluate the extent to which these patterns vary across additional volcanic landforms in East Kalimantan.

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Declaration of AI Use

This manuscript was prepared through the intellectual contributions of the author(s) to the study design, data analysis, interpretation of results, and scholarly content. Grammarly and ChatGPT were used solely to assist with grammatical refinement and reference formatting during manuscript revision. The author(s) accept full responsibility for the accuracy, integrity, and final content of the manuscript.

Competing Interests

Authors have declared that they have no known competing financial interests OR non-financial interests OR personal relationships that could have appeared to influence the work reported in this paper.

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