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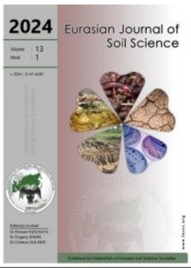

Distribution of soil minerals along the toposequence of Hyang-Argopuro Volcanic Mountain, Jember, Indonesia

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Abstract

The study was conducted in the Hyang-Argopuro volcanic mountain in Jember, Indonesia, with the aim of assessing the distribution of soil minerals along a toposequence and their relationship to soil genesis. Three soil profiles representing the upper, middle, and lower slopes of the toposequence were analyzed. The results revealed that the predominant sand minerals in the soils are opaque minerals, weatherable minerals, amphibole groups, and ferromagnesian minerals. The presence of magnetite, primarily found in the soil profile on the upper slope, suggests the effect of the well-drained topography on its formation. Clay mineral analysis showed that halloysite dominates in soil profile 1, along with traces of gibbsite and cristobalite in the surface horizon. Soil profile 2 is characterized by a combination of halloysite and illite, while kaolinite and illite dominate in soil profile 3. The presence of illite in these soils aligns with previous studies conducted in volcanic regions. The degree of soil development follows the sequence: Soil Profile 2 > Soil Profile 1 > Soil Profile 3. This corresponds to the soil classification, where soil profile 3 is classified as an Alfisol, soil profile 1 as a Mollisol, and soil profile 3 as an Inceptisol. The Andic properties, such as low bulk density and high pH in NaF, observed in soil profile 1 suggest its development from an Andisol. Overall, the study findings highlight the significant influence of basaltic andesite parent material, mountainous topography, and warm and wet climate on the mineral composition and development in the area.

Keywords: Soil development, toposequence, tuff, volcanic minerals.

Introduction

Soils are formed from the interactions of parent material, climate, topography, organism, and time. Parent material, the geologic material from which a soil develops, influences the mineral composition of young soils produced but not the old or highly weathered soils (Chesworth, 1973; Buol et al., 2011; Blume et al., 2016). Likewise, parent material composition affects soil texture. For instance, quartz-rich parent materials such as granite and sandstone produce coarse-textured young soils, while alkaline parent rocks produce fine-textured soils. It has also been shown that the amount of feldspar in the parent rock is directly related to the amount of clay in the soil that is formed (Birkeland, 1984). Moreover, Blume et al. (2016) noted that the direction and intensity of soil development depend strongly on the parent rock's compactness, mineral composition, and texture. Deeper soils form from unconsolidated sediments compared to those neighboring soils from hard rock, even if these have been disintegrated through weathering.

Soil minerals are divided into two groups, namely primary and secondary minerals. Primary minerals are minerals formed from crystallization of magma inside the earth or of lava during volcanic eruption, while secondary minerals result from the alteration of primary minerals (Blume et al., 2016). The actual mineral assemblage in soils may originate from the minerals coming from other rocks and soils transported by air, water, or gravity; from minerals inherited from the parent rock; as relictic materials from paleoenvironments; and as products of neoformation, transformation, and destruction of minerals under the current environment (Stahr, 1994).

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Soil minerals distribution may vary vertically with soil depth and horizontally in the toposequence, a sequence of related soils that vary in topography or physiographic position. The vertical distribution is generally a function of the composition of the parent material, degree of weathering, pedoturbation, and anthropogenic influences. On the other hand, the horizontal distribution of soil minerals in the toposequence is generally the effect of topography and land use (Duchaufour, 1977; Buol et al., 2011). Topography controls the movement of water and materials along the slope (Duchaufour, 1977; Blume et al., 2016). Topography can change the mineralogical arrangement in the soil even though the soil comes from the same parent material. Along the slopes is one of the simplest but most elegant ways to spatially distinguish the reciprocal relationship between soil and topography (Schaetzl and Anderson, 2005).

Limited studies have been done on the distribution of soil minerals in the humid tropics, such as in the Argopuro volcanic mountains in Jember, Indonesia. Research on the distribution of soil minerals is relevant since it can provide new knowledge about the development, characteristics, and nutrient status of soils which in turn are crucial for the sustainable management of soil resources. Thus, the aim of this study was to evaluate the distribution of soil minerals in the toposequence of the Hyang-Argopuro volcanic mountain in Jember, Indonesia, and examine their relationship with soil genesis. By analyzing three soil profiles representing the upper, middle, and lower slopes of the toposequence, we aimed to determine the dominant soil minerals and their variations across the landscape. Additionally, we aimed to investigate the influence of factors such as topography, parent material (basaltic andesite), and climate (warm and wet) on the mineral composition and development of the soils. Understanding the spatial distribution of soil minerals and their associations with soil genesis can provide valuable insights into the formation processes and landscape dynamics of volcanic regions.

Material and Methods

The study was conducted in the Jelbuk Sub-district on the southeastern slope of the mountains of Argopuro. Generally, the shape of the land is undulating with a slope of <3% to hilly with a slope of 25%. The altitude of the study area ranges from 300 masl – 1,110 m asl. Physiographically, the area is part of the footslope and midslope of the Argopuro volcanic complex.

The study area comprises of Argopuro Breccia (Qvab) Formation, an andesitic volcanic breccia, and lava inclusions. This unit is the result of the last Gunung Hyang-Argopuro geological formation activity. Under the Argopuro Breccia (Qvab) unit, there is an Argopuro Tuff unit (Qvat), with tuff as the primary unit consisting of interrupted tuffs, ash tuffs, and glass tuffs. Interrupted tuffs consist of andesite pyroxene compiled rock fragments with porphyritic textures (Sapei et al., 1992). Jelbuk Subdistrict has an average annual rainfall of 2,335 mm with seven rainy months starting from October to April. The climate station used in this study was located 5 km from the furthest sample point (upper slope) location. Annual rainfall data were obtained from the average annual rainfall over the past 15 years (Figure 1).

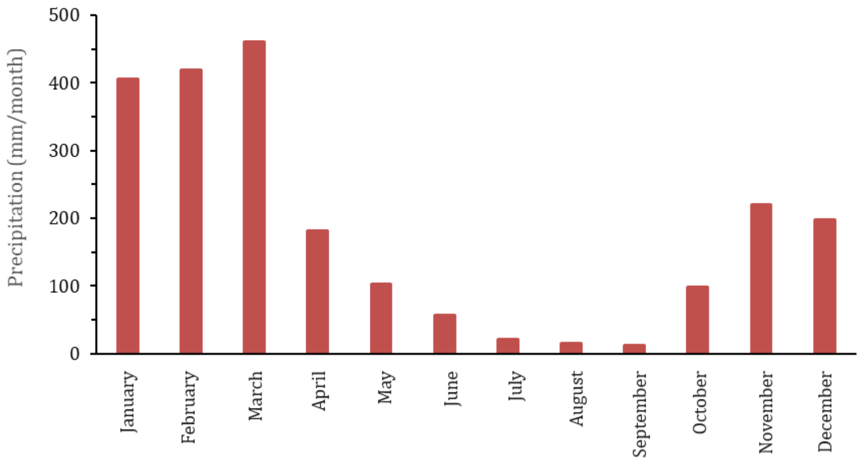
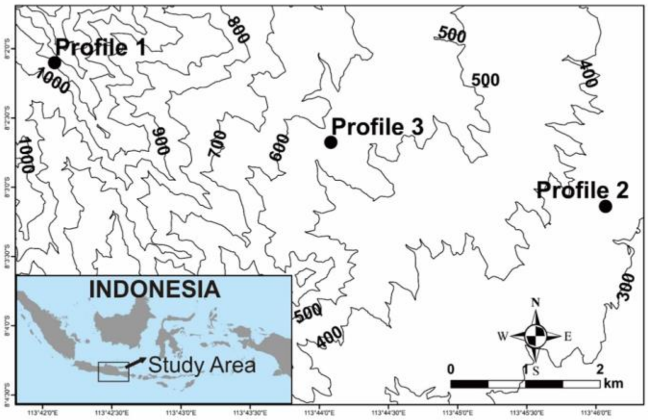


Figure 1. Rainfall distribution in the study area (2000 – 2015)

To select the three (3) soil profiles for the study, a seven (7) km transect was chosen from the upper to the lower slope of the study area (Figure 2a,b). The first soil profile 1 representing the upper slope was dug at an altitude of 1,110 masl with coordinates of 08002'06.07 "S. - 113042'05.17" E. The soil profile 2 representing the middle slope, was excavated at an altitude of 600 m.a.s.l with coordinates of 08002'09.46 "S. - 113043'05.46 E. Soil profile 3 representing the lower slope was located at an altitude of 327 masl and coordinates of 08003'08.31" S - 113045'08.77 E.



Transect map of soil profiles location in the Jelbuk Subdistrict, Jember

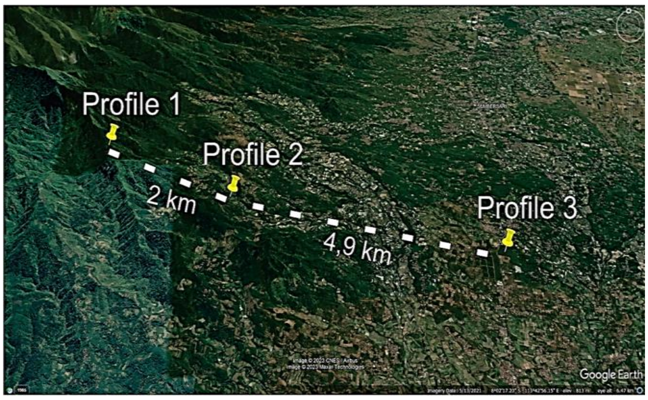


Figure 2b. Aerial map of transect location (Source: Google Earth, accessed in May 2021)

Each soil profile was described following the FAO Guidelines for Soil Description, and then about 1.0 kg of soil samples were collected from each horizon for laboratory soil analysis. The samples were transported to the laboratory, air-dried, freed of rocks and plant debris, ground using a wooden hammer, and sieved using a 2.0 mm mesh sieve. The analyses performed included the actual soil pH measured by mixing soil and aquadest with a ratio of 1: 2.5 m/v, the potential pH is measured by mixing soil with 1 M KCl by a ratio of 1: 2.5 m/v and then reading the pH values with the use of a pH meter (Balai Penelitian Tanah, 2005). Soil texture was analyzed by pipette method after organic matter destruction using a 10% H_2O_2 and clay dispersion using $Na_4P_2O_7 . 10 H_2O$ (Balai Penelitian Tanah, 2005). Bulk density was measured using the core method, and particle density was determined based on measurements of the mass and volume of soil particles. Saturated hydraulic conductivity was measured using laboratory methods (Balai Penelitian Tanah, 2005). The mineral composition of the sand fraction was determined by the line-counting method. Crystalline soil minerals were determined on the Random Powder Specimen using XRD (X-ray diffraction) (Van Reeuwijk, 2002).

Results and Discussion

Soil morphological, physical, and chemical characteristics

Soil horizon differentiation is an essential parameter in evaluating soil development. Results revealed that the horizons arrangement on the upper slope is Ah1 – Ah2 - AB – Bw1 – Bw2, on the middle slope is Ap - AB - Bt1 - Bt2 – Bt3, and on the lower slope is Ah1 – Ah2 - Bw - BC - 2A - 2Bw1 - 2Bw2 (Table 1).

Table 1. Soil morphology in toposequence

Horizon	Soil Depth (cm)	Soil Color (wet)	Soil Texture	Structure	Rooting
Soil Profile 1. Upper slope, the elevation of 1110 m.a.s.l., the slope of <3%, use of primary forest land, bushland cover, and shrubs					
Ah1	0 – 10	7.5 YR 2,5/2	SiCL	Gr	va
Ah2	10 – 24,5	7.5 YR 2,5/3	SiCL	Gr	a
AB	24,5 – 42	7.5 YR 3/3	SiL	Cr	c
Bw1	42 – 71	7.5 YR 3/4	CL	SUB	c
Bw2	71 – 130	10 YR 3/4	SiCL	AB	vf
Soil Profile 2. Middle slope, 600 m.a.s.l elevation, 25% slope, dry land with paddy - maize/soybean - tobacco planting system					
Ap	0 – 11	7.5 YR 3/4	SiCL	Gr	a
AB	11 – 24	7.5 YR 3/5	SiCL	SUB	c
Bt1	24 – 44	7.5 YR 4/6	SiCL	SUB	c
Bt2	44 – 60	7.5 YR 3/4	SiC	SUB	ni
Bt3	60 – 107	5 YR 3/4	SiC	AB	ni
Soil Profile 3. Lower slope, 327mdpl elevation, 5% slope, industrial forest land, pine, and bushland cover					
Ah1	0 – 7	7.5 YR 3/1	L	Gr	va
Ah2	7 – 26	7.5 YR 2,5/2	SiCL	SUB	a
Bw	26 – 48	7.5 YR 3/2	CL	SUB	c
BC	48 – 57	10 YR 4/1	L	Cr	vf
2A	57 – 73	7.5 YR 3/2	SiCL	SUB	vf
2Bw1	73 – 94	7.5 YR 3/2	SiCL	SUB	vf
2Bw2	94 – 150	7.5 YR 2,5/3	SiC	SUB	ni

SiCL = silty clay loam, SiL = silt loam, SiC = silty clay, CL = clay loam, L = loam, Gr = granular, Cr = crumb, SUB = sub angular blocky, AB = angular blocky, va = very abundant, a = abundant, c = common, f = few, vf = very few, ni = not identified

These results suggest that the soil on the upper slope is moderately developed, as indicated by the presence of a cambic B horizon (Bw). In contrast, on the middle slope, the soil is well developed, as reflected by the presence of an argillic horizon (Bt). Argillic horizons are horizons of illuvial accumulation of layer silicate clays and are found in well-developed or mature soils (Buol et al., 2011). Moreover, the results indicate that the soil on the lower slope is poorly developed, as shown by the lithologic discontinuity in the soil profile. The lower slope (a footslope) is a depositional surface which suggests that soil materials are periodically deposited on the existing soil, thereby retarding soil development. Figure 3 presents the depth functions of sand, silt, and clay which also show the significant increase of clay (argillic horizon) in the lower horizons of soil profile 2, and the irregular decrease with depth of sand, silt, and clay in soil profile 3.

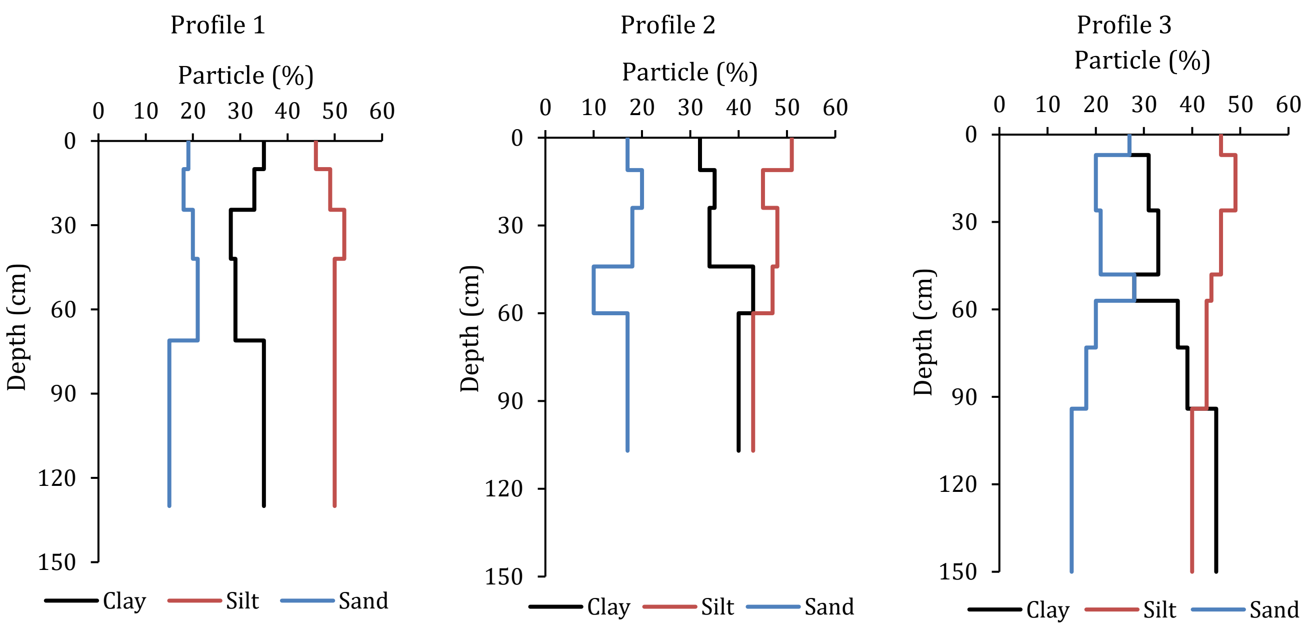


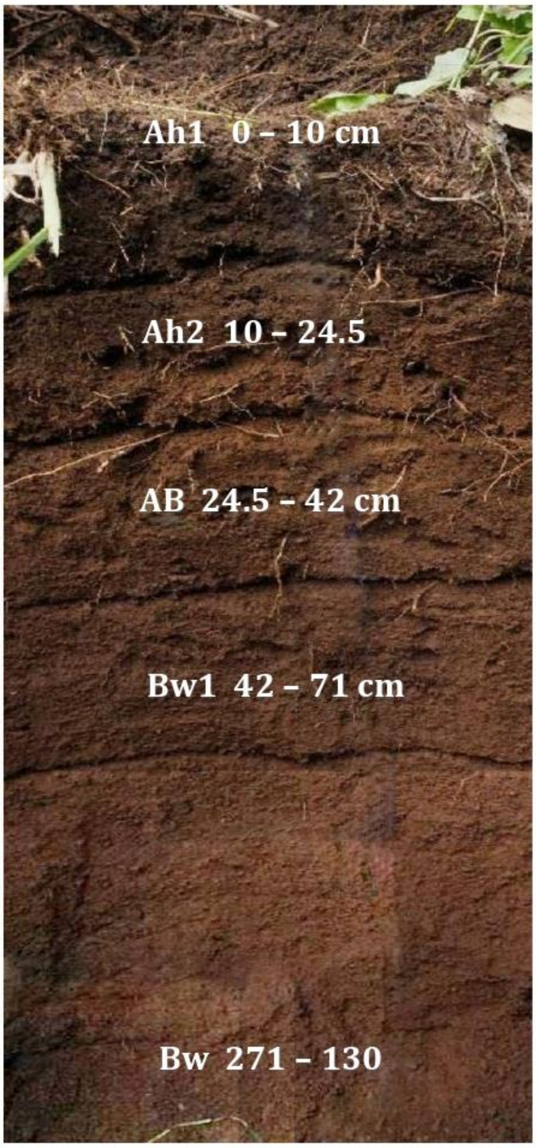
Figure 3. Depth function of sand, silt, and clay particles in the soils studied

Soil color reflects the soil composition as well as the past and present conditions of the soil (Blume et al., 2016). The dominant soil color hue of the volcanic toposequence evaluated is 7.5 YR (Table 1). Colors other than 7.5YR are only found in the Bw2 horizon (10 Y.R.) of soil profile 1, the Bt3 horizon (5YR) of soil profile 2, and BC horizons (10YR) of soil profile 3. Shoji et al. (1993) reported that volcanic soils in Japan have color hues ranging from 7.5YR to 10YR. Miehlich (1991) observed that most volcanic soils from Mexico he studied had color hues of 7.5YR and 10YR. The same trend was observed for the volcanic soils in Leyte, Philippines (Asio, 1996). Details of the morphology of the soil profiles are found in Figure 4, 5 and 6.

Table 2 presents the clay content and other physical properties of soils developed from igneous rocks. It shows that the clay content of the soils in the toposequence studied ranges from 27 to 45 percent. The textural class ranges from silty clay loam in horizon A to silty clay loam to silty clay in horizon B. The soil structure is granular in the A horizons, sub-angular blocky, and angular blocky in the B horizons. Such soil structures are common in volcanic soils (Miehlich, 1991; Shoji et al., 1993; Asio, 1996). The presence of roots in a soil horizon is a good indicator of the suitability of the soil for the development of the plant root systems and is directly related to the fertility status of the soil. As can be expected, the highest number of roots is found in the A horizons of all the soils evaluated.

The bulk density values in soil profile 1 are less than 1.0 g cm^{-3} indicating a very porous soil (average of 64 percent). Such low bulk density values of Inceptisols from volcanic rocks in Taiwan were attributed to high inter- and intraaggregate voids caused by the high organic matter content and isovolumetric weathering (Miehlich, 1991; Chen et al., 2001). It can be partly attributed to the high amounts of halloysite which in itself is highly porous (Quantin, 1990). Soil profiles 2 and 3 have average bulk density values of 1.18 g cm^{-3} and 1.21 g cm^{-3}, respectively. These values indicate a relatively porous soil favorable to root development and water movement. The results also showed that the particle density values of the soils range from 1.69 to 2.43 g cm^{-3} which are way below the widely used standard value of 2.65 g cm^{-3}. The K_S values are highest in soil profile 1 and lowest in soil profile 2 which follows the same order of the soil porosity values. This means that the more porous soil resulted in higher saturated hydraulic conductivity values.

Coordinates	:	08⁰02'06.07" S - 113⁰42'05.17" E	Epipedon	:	Mollic
Altitude	:	1110 masl	Endopedon	:	Cambic
Slope	:	0 - 3 %	Soil Classification		
Land Use	:	Primary Forest	Soil Taxonomy	:	Andic Hapludolls
Land Cover	:	Shrubs	FAO	:	Andic Chernozem (Siltic)
Surface Rocks	:	Not Rocky	Indonesian system	:	Molisol Haplik



DESCRIPTION

Ah1
clear boundary layer, oblique flat shape, many root, silty clay loam, granular structure, fine size, weak, non sticky wet consistency, loose moist consistency, loose dry consistency, soil color 7.5 YR $^{2,5}/_{3}$, pH H_2O 4.76; KCl 4.25; NaF 10.98, no nodules.

Ah2
clear boundary layer, oblique flat shape, many root, silty clay loam, granular structure, fine size, weak, non sticky wet consistency, loose moist consistency, loose dry consistency, soil color 7.5 YR $^{2,5}/_{3}$, pH H_2O 4.76; KCl 4.25; NaF 10.98, no nodules.

AB
clear boundary layer, oblique flat shape, few root, silty loam, crumb structure, fine, weak, non sticky wet consistency, loose moist consistency, loose dry consistency, soil color 7.5 YR $^{3}/_{3}$, pH H_2O 4.74; KCl 4.37; NaF 11.17, tuffs found, few, no nodules.

Bw1
slightly diffuse boundary layer, oblique flat shape, few root, clay loam, sub angular blocky, fine, weak, slightly sticky wet consistency, slightly firm moist consistency, soft dry consistency, soil color 7.5 YR $^{3}/_{4}$, pH H_2O 4.79; KCl 4.32; NaF 9.24, nodules.

Bw2
diffuse boundary layer, oblique flat shape, very little root, silty clay loam, angular blocky structure, fine, weak, slightly sticky wet consistency, firm moist consistency, slightly hard dry consistency, soil color 10 YR $^{3}/_{4}$, pH H_2O 4.45; KCl 3.97; NaF 9.40, no nodules.

Ah1
clear boundary layer, oblique flat shape, many root, silty clay loam, granular structure, fine size, weak, non sticky wet consistency, loose moist consistency, loose dry consistency, soil color 7.5 YR $^{2,5}/_{3}$, pH H_2O 4.76; KCl 4.25; NaF 10.98, no nodules.

Figure 4. Soil morphology of soil profile 1

Coordinates	:	08002’09.46”S - 113043’05.46”E
Altitude	:	600 masl
Slope	:	25 %
Land Use	:	Upland
Land Cover	:	Tobacco
Surface Rocks	:	A little rocky

Epipedon	:	Ocric
Endopedon	:	Argillic
Soil Classification		
Soil Taxonomy	:	Typic Hapludalf
FAO	:	Hydragic, Irragric Anthrosols (Siltic)
Indonesian system	:	Mediteran Haplik

DESCRIPTION

Ap

clear boundary layer, Wavy, root slightly many, silty clay loam, wet consistency is slightly sticky, friable moist consistency, slightly hard dry consistency, soil color 7.5 YR $^3/_4$, pH H_2O 5.16; KCl 4.49; NaF 9.29, no nodules.

AB

slightly diffused boundary layers, wavy, root slightly many, silty clay loam, sub angular blocky structure, very fine, weak, slightly sticky wet consistency, friable moist consistency, slightly hard dry consistency, soil color 7,5 YR $^3/_5$, pH H_2O 5.41; KCl 4.52; NaF 9.47, no nodules.

Bt1

slightly diffused boundary layers, wavy, few root, silty clay loam, sub angular blocky structure, fine, weak, slightly sticky wet consistency, firm moist consistency, slightly hard dry consistency, soil color 7.5 YR $^4/_6$, pH H_2O 6.12; KCl 5.37; NaF 9.40, Fe and Mn nodules, few.

Bt2

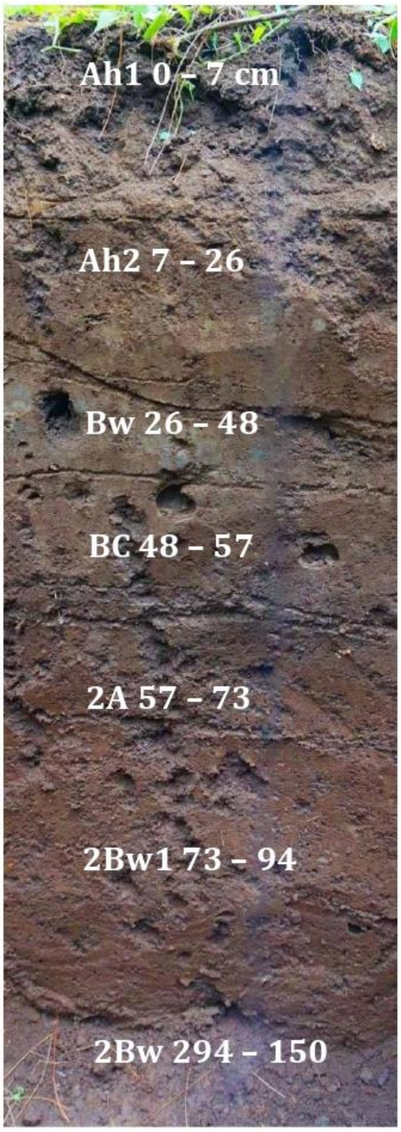
slightly diffused boundary layers, wavy, no root, silty clay, sub angular blocky structure, fine, weak, sticky wet consistency, firm moist consistency, hard dry consistency, soil color 7.5 YR $^3/_4$, pH H_2O 5.96; KCl 5.08; NaF 9.34, Fe and Mn nodules, few.

Bt3

clear boundary layers, wavy, no root, silty clay, sub angular blocky structure, fine, weak, sticky wet consistency, firm moist consistency, hard dry consistency, soil color 5 YR $^3/_4$, pH H_2O 5.97; KCl 4.99; NaF 9.22, Fe and Mn nodules, few

Figure 5. Soil morphology of soil profile 2

Coordinates	:	08003’08.31”S - 113045’08.77”E	Epipedon	:	Umbric
Altitude	:	325 masl	Endopedon	:	Cambic
Slope	:	5 %	Soil Classification		
Land Use	:	Industrial Plantation Forest	Soil Taxonomy	:	Typic Eutrudepts
Land Cover	:	Pine	FAO	:	Haplic Cambisols (Eutric, Humic, Siltic)
Surface Rocks	:	A little rocky	Indonesian system	:	Kambisol Eutrik



DESCRIPTION

Ah1

clear boundary layer, wavy, slightly many root, silty clay loam, crumb structure, non sticky wet consistency, soft moist consistency, soft dry consistency, soil color 7,5 YR 3/1, pH H2O 5.31; KCl 4.40; NaF 9.25, no nodules

Ah2

clear boundary layer, wavy, root many, silty clay loam, sub angular blocky structure, fine, weak, slightly sticky wet consistency, soft moist consistency, soft dry consistency, soil color 7.5 YR $^{2,5}/_{2}$, pH H_2O 5.62; KCl 4.71; NaF 9.51, no nodules

Bw

clear boundary layer, oblique flat shape, few root, clay loam, sub angular blocky structure, fine, weak, slightly sticky wet consistency, friable moist consistency, soft dry consistency, soil color 7.5 YR $^{3}/_{2}$, pH H_2O 5.83; KCl 4.74; NaF 9.40, no nodules

BC

clear boundary layer, wavy, very few root, loam, crumb structure, fine, weak, non sticky wet consistency, friable moist consistency, loose dry consistency, soil color 10 YR $^{4}/_{1}$, pH H_2O 5.86; KCl 4.75; NaF 9.36, there are tuffs, few, no nodules

2A

clear boundary layer, oblique flat shape, very few root, silty clay loam, sub angular blocky structure, fine, weak, slightly sticky wet consistency, firm moist consistency, soil color 7.5 YR $^{3}/_{2}$, pH H_2O 6.16; KCl 4.88; NaF 9.28, no nodules

2Bw1

clear boundary layer, oblique flat shape, silty clay loam, sub angular blocky structure, fine, weak, slightly sticky wet consistency, firm moist consistency, soft dry consistency, soil color 7.5 YR $^{3}/_{2}$, pH H_2O 5.89; KCl 4.88; NaF 9.33., Fe and Mn nodules, few

2Bw2

clear boundary layer, oblique flat shape, no root, silty clay, sub angular blocky structure, fine, weak, slightly sticky wet consistency, firm moist consistency, soft dry consistency, soil color 7.5 YR $^{2,5}/_{3}$, pH H_2O 6.01; KCl 4.75; NaF 9.41, Fe and Mn nodules, few

Figure 6. Soil morphology soil Profile 3

Table 2. Soil physical characteristics

	Horizon	Depth (cm)	Texture			BD (g/cm^3)	PD (g/cm^3)	Porosity (%)	K.S. (cm/day)
			Sand (%)	Silt (%)	Clay (%)				
Soil Profile 1	Ah1	0 - 10	19	46	35	0.72	1.87	61	267.5
	Ah2	10 - 24.5	18	49	33	0.67	2.04	67	563.7
	AB	24,5 - 42	20	52	28	0.78	2.14	64	372.3
	Bw1	42 - 71	21	50	29	0.73	2.34	69	129.4
	Bw2	71 - 130	15	50	35	0.96	2.43	60	64.3
Soil Profile 2	Ap	0 - 11	17	51	32	1.32	1.69	22	9.3
	AB	11 - 24	20	45	35	1.11	2.01	45	38.3
	Bt1	24 - 44	18	48	34	1.10	1.88	41	38.7
	Bt2	44 - 60	10	47	43	1.28	2.61	51	22.7
	Bt3	60 - 107	17	43	40	1.09	1.96	44	24.9
Soil Profile 3	Ah1	0 - 7	27	46	27	1.31	1.96	33	149.2
	Ah2	7 - 26	20	49	31	1.22	2.29	47	67.9
	Bw	26 - 48	21	46	33	1.17	2.12	45	68.8
	BC	48 - 57	28	44	28	1.15	2.31	50	24.9
	2A	57 - 73	20	43	37	1.30	2.38	45	54.4
	2Bw1	73 - 94	18	43	39	1.16	2.26	49	25.7
	2Bw2	94 - 150	15	40	45	1.19	2.26	47	83.7

BD = bulk density, PD = particle density, KS = saturated hydraulic conductivity

Table 3 presents the soil chemical characteristics in the volcanic toposequence studied. The soil pH (H_2O) values of the three soil profiles range from 4.45 to 6.16 while pH (KCl) ranges from 3.97-5.37. Soil profile 1 appears to be more acidic than the other soil profiles. The lower pH (KCl) values relative to pH(H_2O) indicate that the net charge of the soil colloids in the three soil profiles is negative (-) according to the delta pH principle introduced by Mekaru and Uehara (1972). Results also revealed that the pH(NaF) are all above 9.0. The pH(NaF) of soil profile 1 ranges from 9.24 to 11.17 with the upper half meter showing values above the 9.5 limit for andic materials (Shoji et al., 1993; Buol et al., 2011). The pH(NaF) of soil profiles 2 and 3 range from 9.22 to 9.47 and 9.28 to 9.51, respectively. The pH(NaF) is used as an indicator of the abundance of active Al and Fe compounds as well as the P sorption capacity of soils. Soil organic carbon content is higher in the surface horizons of three soil profiles with soil profile 1 showing the highest amount. This is also reflected by the darker color of the surface horizons compared to the subsurface horizons. The lithologic discontinuity indicated by the horizons of soil profile 3 is also reflected by the irregular decrease of organic carbon content with soil depth.

Table 3. Soil chemical characteristics

	Horizon	Soil Depth (cm)	pH			Org C (%)
			H_2O	KCl	NaF	
Soil Profile 1	Ah1	0 - 10	4.91	4.21	9.62	4.55
	Ah2	10 - 24.5	4.76	4.25	10.98	2.70
	AB	24,5 - 42	4.74	4.37	11.17	1.96
	Bw1	42 - 71	4.79	4.32	9.24	1.10
	Bw2	71 - 130	4.45	3.97	9.40	0.66
Soil Profile 2	Ap	0 - 11	5.16	4.49	9.29	1.41
	AB	11 - 24	5.41	4.52	9.47	1.34
	Bt1	24 - 44	6.12	5.37	9.40	1.21
	Bt2	44 - 60	5.96	5.08	9.34	0.96
	Bt3	60 - 107	5.97	4.99	9.22	0.96
Soil Profile 3	Ah1	0 - 7	5.31	4.40	9.25	2.92
	Ah2	7 - 26	5.62	4.71	9.51	1.34
	Bw	26 - 48	5.83	4.74	9.40	1.20
	BC	48 - 57	5.86	4.75	9.36	0.60
	2A	57 - 73	6.16	4.88	9.28	0.92
	2Bw1	73 - 94	5.89	4.88	9.33	0.97
	2Bw2	94 - 150	6.01	4.75	9.41	076

Sand Mineralogy

Sand is a soil particle measuring 2 mm - 0.02 mm in diameter. Blume et al. (2016) stated that the sand fraction consists mainly of stable igneous and metamorphic minerals such as quartz, potash feldspars, micas, and numerous heavy minerals that remain after weathering. Thus, the mineralogy of the sand fraction generally reflects the mineral composition of the parent rock. In the present study, microscopic examination of sand samples from the three soil profiles revealed that the opaque minerals are the most abundant, followed by the rock fragments, then by pyroxene (augite and hyperstene), Ca - Na plagioclase (andesine and labradorite), weathered mineral, amphibole (brown and green hornblende), and mineral series from ferrous magnesia (olivine, tourmaline, and epidote) (Table 4). Moreover, the sporadic presence of iron concretions, bytownite, and tourmaline can be observed in all soil profiles. Sporadic occurrence of olivine, epidote, and brown hornblende is observable in soil profile 3.

Table 4. Sand mineral analysis

Depth (cm)	Horizon	Opaque	Zirkon	Clear Quartz	Turbid Quartz	Iron Concretion	Zeolite	Weathered Mineral	Rock Fragments	Volcanic Glass	Oligoclase	Andesine	Labradorites	Bytownite	Green Hornblende	Brown Hornblende	Augite	Hypersthene	Olivine	Epidotes	Tourmaline	Total (100%)
Soil Profile 1																						
0-10	Ah	47	-	-	-	sp	-	8	15	2	sp	sp	9	sp	3	-	7	9	-	-	sp	100
24-42	A2	52	-	-	-	-	-	6	19	3	-	-	7	sp	3	-	4	6	-	-	sp	100
71-130	Bw2	46	-	-	-	sp	-	5	21	3	sp	sp	10	sp	4	sp	6	5	-	-	sp	100
Soil Profile 2																						
0-11	Ap	32	sp	sp	sp	sp	sp	15	22	4	-	-	11	1	2	sp	7	6	-	-	sp	100
24-44	Bt2	47	-	-	-	sp	-	11	20	2	-	-	8	sp	2	-	3	5	-	-	sp	100
60-107	B	38	sp	-	-	sp	-	13	18	4	-	sp	10	sp	4	-	5	8	-	-	sp	100
Soil Profile 3																						
7-26	A1	30	-	-	-	sp	-	2	27	2	-	1	16	sp	7	sp	6	8	sp	sp	1	100
48-57	BC	34	-	-	-	sp	-	1	32	1	-	sp	12	sp	5	sp	7	8	sp	sp	sp	100
94-150	2Bw2	42	-	sp	sp	sp	-	sp	28	sp	-	sp	15	sp	4	sp	4	7	sp	sp	sp	100

SP: Sporadic on orientation found, but not offending line counting; - : Not found on orientation

Opaque minerals are minerals that do not transmit light in thin sections and they have high density. Common members of this mineral are magnetite and ilmenite. Based on the geological map of East Java, several studies indicate that the rock composition of the Hyang mountain range (Argopuro, Raung, and Ijen) is basaltic andesite (Sapei et al., 2009; Indarto et al., 2011; Abdullah, 2016). Abdullah (2016) revealed that the opaque mineral in soils developed from the Raung volcanic material is magnetite. From the mineral composition found in this present study, it can be assumed that the opaque mineral detected is also magnetite which according to Haldar and Tisljar (2014) is common in igneous rocks.

The highest number of opaque minerals is found in soil profile 1, followed by soil profile 2, and the lowest is in soil profile 3. The trend shows a decrease from the upper slope to the foot slope, which can be explained by the fact that opaque minerals have a high density, such that their amount will increase towards the caldera upslope. In addition, the opaque mineral content is higher, the higher is the sand content. This pattern also occurs in rock fragments. The abundance of magnetite in the upper slope (soil profile 1) can also be explained by the well-drained condition of the site. Ahmed and Maher (2018) reported that the dominance of magnetite shows that its formation occurs in well-drained and oxidizing soils.

Rock fragments are an aggregate of several minerals with a specific composition, so rock fragments are put into a separate group in the examination of the mineral composition of sand. The amount of rock fragments in the soil profile is directly proportional to the sand content. This is because rock fragments will contribute to the sand content in the soil.

Clay Mineralogy

Clay minerals are secondary minerals derived from the alteration of primary minerals and have a size of <0.002 mm. The XRD analysis showed that the clay in soil profile 1 is dominated by halloysite with a few accompanying gibbsite and cristobalite (Table 5, Figure 7). Soil profile 2 is dominated by halloysite and illite, whereas soil profile 3 is dominated by kaolinite and illite. Illite is a non-expanding clay mineral belonging to the 2:1 type, whereas halloysite and kaolinite belong to the 1:1 type of clay mineral. Studies on the volcanic soils of Mexico (Miehlich, 1991), Taiwan (Chen et al., 2001), and the Philippines (Asio, 1996; Navarrete et al., 2009) revealed the common occurrence of halloysite and kaolinite.

Table 5. Clay mineralogy of the soils

Horizon	Depth (cm)	Halloysite (10Å)	Halloysite (7.2Å)	Kaolinite	Gibbsite	Cristobalite	Illite
Soil Profile 1							
Ah1	0 – 10	-	+++	-	+	+	-
AB	24.5 – 42	-	+++	-	-	-	
Bw2	71 – 130	+++					++
Soil Profile 2							
Ap	0 – 11	-	+++	-	-	-	++
Bt1	24 – 44	-	++	-	-	-	++
Bt3	60 – 107	-	++	-	-	-	+++
Soil Profile 3							
Ah1	7 – 26	-	-	++++	-	-	(+)
BC	48 – 57	-	-	++	-	-	++
2Bw2	94 – 150	-	-	++	-	-	+++

Note: ++++ Predominant; +++ Dominant; ++ Moderate; + Few; (+) Very few; - Nothing

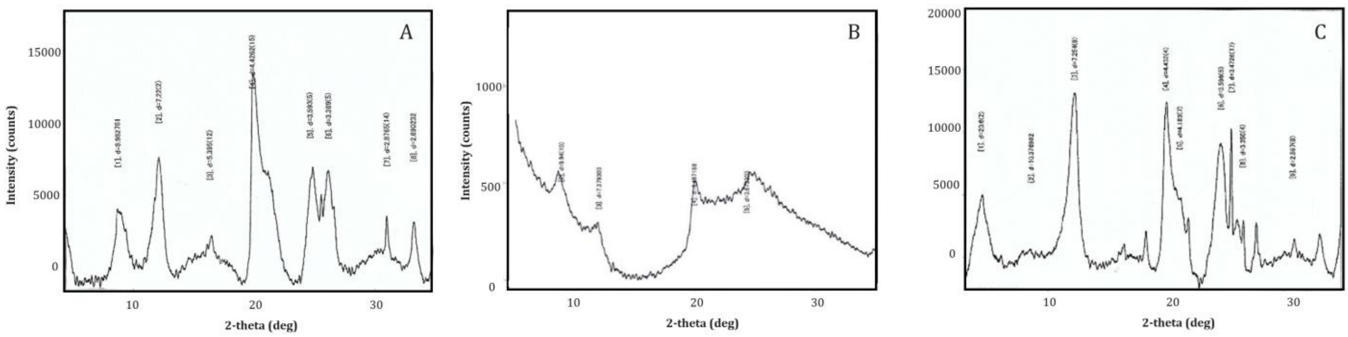


Figure 7. XRD analysis of top layer clay minerals from soil profile 1 (A), soil profile 2 (B), and soil profile 3 (C).

Results also revealed that halloysite mineral is dominant in the upper layers of soil profiles 1 (upper slope) and 2 (middle slope) but is not present in soil profile 3 on the footslope. Halloysite is a form of kaolinite in which water is held between structural units in the basal plane. In a completely hydrated state, halloysite exhibits an intense peak at 10 Å. This corresponds to a single sheet of water molecules ~2.8 Å thick between the 7.2 Å layers. The interlayer water is, however, very labile so that halloysite is most commonly observed in a more dehydrated form which displays a diffraction peak of 7.2 Å (Hillier and Ryan, 2002; Bohn et al., 2001). Halloysite can come from the transformation of amorphous minerals such as allophane and imogolite. The abundance of halloysite minerals in soil profile 1 suggests that the soil developed from amorphous minerals that characterize Andisols. The high NaF-pH and low H_2O-pH also point to the Andisol origin of this soil. Prasetyo et al. (2009) argued that the low allophane in soils was due to the development of the soil and the desilification process so that the allophane content was reduced and formed halloysite hydrate crystalline minerals.

The halloysite of 10 Å is found only on the Bw2 horizon in soil profile 1, while the halloysite with 7 Å diffraction peak is the one found in the Ah horizons of soil profiles 1 and 2. Soil profile 3 is dominated by kaolinite (7 Å) particularly on the surface horizon. The greater abundance of kaolinite in tropical soils lies in the stage of weathering of the soils. The mineral feldspar can progressively weather to mica, kaolinite, and gibbsite. Warm and humid conditions in the tropics facilitate a rapid removal of potassium and dissolved silica so that feldspar and mica quickly turn into kaolinite and gibbsite (Uehara and Gillman, 1981). Kaolinite is generally formed by the weathering of 2:1 mineral, but some researchers report that kaolinite can also be formed through other processes. Jahn (1988) showed that kaolinite can be formed through halloysite kaolinization. Hydration and carbonation can cause the alteration of Ca-Na feldspar to become clay (Hunt, 1976).

$$CaAl_2Si_2O_8.\ 2NaAlSi_3O_8 + 4H_2CO_3 + 2(nH2O) \longrightarrow 2Al_2(OH)Si_4O_{10}nH_2O\ (clay) + Ca(HCO_3)_2 + 2NaHCO_3$$

Furthermore, some studies cited by Buol et al. (2011) showed that kaolinite can be formed by altering albite minerals.

$2NaAlSi_3O_8$ (albite) + $2H_2CO_3$ + $9H_2O \longrightarrow Na^+ + 2HCO^-_3 + 4H_4SiO_4 + Al_2Si_2O_5(OH)_4$ (kaolinite).

Cristobalite is a silica (SiO2) mineral member, while gibbsite is an aluminum hydroxide mineral ($Al(OH_3)$). Gibbsite can be formed directly through the weathering of primary minerals (Wada and Aomine, 1966; Prasetyo et al., 2009). Cristobalite can be known through XRD analysis with diffraction peaks of 4.26 and 3.34 Å. Gibbsite displays a diffraction peak of 4.82 Å.

Interestingly, illite (10 Å) is present in few to moderate amounts in all soil profiles and tends to increase with soil depth. Several hypotheses have been proposed to explain the occurrence of illite in volcanic soils (Shoji et al., 1993). One is that it is an alteration product from mafic minerals such as pyroxene, amphiboles, and micas in parent material. Second, it is formed from amorphous materials as product of an advanced stage of weathering. Third, hydrothermal alteration products. Fourth is the solid-state transformation of volcanic glass by K retention (Shoji et al., 1993).

Soil Genesis

Soil formation is influenced by climate, parent material, organism, topography, and time. Results of the study clearly indicate the major influence of climate, parent material, and topography on the formation of the soils. The hot and wet humid tropical climate favored fast weathering and soil formation resulting in the formation of kaolinite, halloysite, and gibbsite from the primary minerals present in the basaltic andesite parent rock. The high rainfall not only enhanced weathering but also leaching of ions released during chemical weathering and transport of soil materials from the upper slopes to the lower slopes. The relatively fast weatherability of the parent rock also contributed to the fast weathering and soil development. The mountainous topography not only enhanced drainage and leaching process but also the transport of soil materials, which led to the lithologic discontinuity observed on soil profile 3.

The degree of soil development can be evaluated based on soil profile morphology, particularly horizonation, degree of weathering, loss and gain of elements, and clay mineralogy (Duchaufour, 1977; Birkeland, 1984; Buol et al., 2011). It is also possible to use the presence of resistant and weathered minerals, as Alam et al. (2011) recently used on the soil development from weathered ultramafic rocks in two toposequences in Southeast Sulawesi. Jackson et al. (1948) published a pioneering work on the weathering sequence of soils based on clay mineralogy. They reported that illite indicates stage 7 while kaolinite and halloysite indicate stage 10 out of 11 stages of weathering they have observed.

Based on the above indicators, the degree of soil development of the soils evaluated is: Soil Profile 2>Soil Profile 1>Soil Profile 3. This also agrees with the soil classification of the soils in that Soil Profile 3 is an Alfisol, Soil Profile 1 is a Mollisol, and Soil Profile 3 is an Inceptisol. Finally, the presence of Andic properties such as low bulk density and high pH in NaF of soil profile 1 tends to indicate that this soil developed from an Andisol similar to what was reported in Taiwan by Chen et al. (2001).

Conclusion

The soils in the volcanic toposequence are dominated in their sand fraction by opaque minerals, weatherable minerals, amphibole groups, and ferromagnesian. The abundance of the opaque mineral (mainly magnetite) in the soil profile on the upper slope suggests the effect of a well-drained topography on its formation. In terms of clay minerals, soil profile 1 is dominated by halloysite with a few gibbsite and cristobalite on the surface horizon, soil profile 2 by halloysite and illite, and soil profile 3 by kaolinite and illite. The presence of illite in the two of the soils studied agrees with the findings of previous studies in other volcanic regions. The degree of soil development of the soils evaluated is: Soil Profile 2>Soil Profile 1>Soil Profile 3. This appears to confirm with the soil classification of the soils in that Soil Profile 3 is an Alfisol, Soil Profile 1 is a Mollisol, and Soil Profile 3 is an Inceptisol. The presence of Andic properties such as low bulk density and high pH in NaF of soil profile 1 tends to indicate that this soil developed from an Andisol. Lastly, the results obtained can be valuable for land management practices, such as soil conservation, agricultural planning, and land-use decision-making in volcanic landscapes. Understanding the mineralogical characteristics and soil development patterns can support optimizing soil fertility, water management, and sustainable land-use practices in similar volcanic regions.

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