

MINERALOGICAL AND CHEMICAL CHARACTERISTICS OF SPodosOLS IN TOBA HIGHLAND, NORTH SUMATRA

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ABSTRACT

Spodosols are problem soils due to coarse texture, acid soil reaction, low nutrient status, and low soil moisture retention. About 2.16 million ha of Spodosols (1.1% of the Indonesian land areas) distributed in lowland and highland areas in Kalimantan, Sumatra, Sulawesi, and Papua. Spodosols of the Toba highland areas require special attention because these forested lands are gradually cleared, but then abandoned because they are not suitable for agricultural development, causing land degradation. This study aimed to evaluate mineralogical and chemical characteristics of Toba highland Spodosols, North Sumatra, and their implication on agricultural development. Three pedons of the Toba highland Spodosols from Humbang Hasundutan regency were studied, consisted of soils developed from volcanic sand overlying liparite tuff under the influence of low temperature and high rainfall. Field observation was conducted in January 2008. Fifteen soil samples were collected from the three pedons based on the depth of soil horizon. Results indicated that the formation of these Spodosols were influenced by parent material, high elevation (1676-1821 m above sea level), and by high amount of rainfall (2167 mm). The Spodosols in Toba highland were still in the early stage of development as characterized by shallow effective soil depth (22-23 cm), domination of weatherable minerals (39-81%) in the sand fraction and dominated by amorphous mineral as shown by sum of $A1 + 1/2 Fe$ extracted by ammonium oxalate as much as 0.6-12.8%. The Spodosols were also characterized by coarse texture (66-95% sand fraction in E and B horizons), high organic-C content (1.4-37.7%), acid soil reaction (pH 3.7-5.3), very high K_2O in Oa horizon (552-933 mg kg^{-1}) and B spodic or C horizon (812-2028 mg kg^{-1}), and low base saturation (< 5%). The existence of biological processes in the surface layer was indicated by accumulation of exchangeable bases (0.88-1.14 cmolc kg^{-1} in Oa horizon and 0.09-0.25 cmolc kg^{-1} in B horizon), P_2O_5 (181-298 mg kg^{-1} in Oa horizon and 3-24 mg kg^{-1} in E horizon), and K_2O (552-933 mg kg^{-1} in Oa horizon and 13-30 mg kg^{-1} in E horizon). However, these nutrients were easily leached after deforestation. With the sandy texture, loose structure, and no vegetation cover, the erosion hazard is high in the deforested areas. Therefore, lands with Spodosols of the Toba highland, especially are not recommended for agricultural development, rather they should be kept as forest lands.

[**Keywords:** Spodosols, weatherable minerals, amorphous minerals, Toba highland, North Sumatra]

INTRODUCTION

Spodosols or better known as Podzols are soils with B spodic horizon, E albic horizon and do not have plagen epipedon, argillic horizon and kandic horizon, but may have cementation horizons such as fragipan, duripan or placic (Soil Survey Staff 2006). The widest distribution of Spodosols is in northern part of Russia and Canada (Mc. Keague *et al.* 1983). In Indonesia, Spodosols are distributed in Kalimantan, Sumatra, Sulawesi and Papua, with the total area of about 2.16 million ha or 1.1% of Indonesian land area (Subagjo *et al.* 2000).

A Spodosol profile consists of (1) A horizon, an organic-mineral surface horizon with dark color; (2) E albic horizon, the eluviation horizon with pale color; (3) B spodic horizon, the iluviation horizon with reddish dark or black color, consist of organic matter enriched by amorphous aluminum with or without iron; and (4) C horizon that is sandy parent material (Mc Keague *et al.* 1983; Buurman *et al.* 2007).

A spodic horizon was formed through Fe and Al transportation with organic complex from surface horizon to the deeper horizon. There were three theories of spodic horizon formation. First, the *fulvate theory*, that unsaturated fulvate acid in the top soil dissolved Fe and Al from primary or secondary minerals and precipitated in the lower horizon with a certain C/metal ratio (Peterson 1976 in Buurman 1984). Second, the *allophane theory*, that by increasing soil pH, Fe and Al were transported to the B horizon as positively charged silicate sols, where they precipitate as amorphous allophane and imogollite. The organic matter would precipitate with allophane to form spodic horizon (Farmer *et al.* 1980 in Buurman 1984). Third, the *low molecular weight acids theory*, that the low molecular weight acids play the role for the transport of Fe and Al to lower horizon, and the precipitation occurs after breakdown of the carrier by microorganism (Lundstrom *et al.* 1995 in Buurman

1984). Sols amorphous Si-Al-Fe is not stable in complex condition with organic acid, so that the formation of spodic horizon tends to happen following the first and third theories, while the second theory is possible but less likely (Buurman and van Reeuwijk 1984).

Buurman and Jongmans (2005) explained that accumulation of organic matter complex in B horizon is not necessarily due to saturation of organic complexes, but may occur as results of microbial decay of organic carrier and be remobilized by supply of fresh dilution organic carbon (DOC). In the mineral rich soil, DOC is broken down rapidly by microbial activities. On the contrary, in the poor mineral soil with poor drainage, the breakdown of DOC is inhibited by Al and Fe complexes, acidity, and lack of oxygen.

Spodosols mainly distributed in those areas rich in quartz sand with shallow ground water fluctuation (Mc. Keague *et al.* 1983; Soil Survey Staff 2006). Spodosols in the humid tropic areas are generally characterized by low content of weatherable minerals and have an E albic horizon which can reach 200 cm thick (Buurman 1986). In the mountain or highland areas, Spodosols could be found on chemically richer parent materials, the continually wet climate, but the low temperature due to the high elevation (Mohr *et al.* 1972). These conditions apply for Toba Spodosols, which were derived from volcanic materials rich in weatherable minerals, wet climate, and low temperature because of high elevation (> 1600 m asl). The Toba highland Spodosols have different characteristics compared with general Spodosols in the lowland areas. In the lowland area, the Spodosols were generally derived from quartz sand deposits, poor of weatherable minerals, and occurred in a higher temperature.

Spodosols is actually one of problem soils in the world. As long as the soil covered by forest vegetation, there will be no problem. Deforestation makes the soils become denuded, and very easily eroded. There was no potential use of the soil for agricultural purpose due to very low weatherable minerals, coarse texture, very low nutrient status, very low moisture retention, and shallow effective soil depth (hard pan), and thus the area should be conserved.

This study aimed to characterize mineralogical and chemical characteristics of Toba highland Spodosols, North Sumatra, and their implication on agricultural development of these areas.

MATERIALS AND METHODS

Three pedons JH 622 (98°37'44" East Longitude and 2°25'14" North Latitude), KR 1268 (98°37'19" East

Longitude and 2°24'34" North Latitude), and UG 976 (98°37'15" East Longitude and 2°27'27" North Latitude) around Toba Lake in Humbang Hasundutan Regency, North Sumatra were chosen to represent Spodosols from highland. Total acreage of these areas are estimated around 4356 ha as complex with Fragiudepts, Hapludands, and Durudands. The soils are derived from volcanic sand overlying liparite tuff, located at 1676-1821 m above sea level (asl), on the volcanic highland (plateau) with flat to slightly rolling relief, under tropical rain forest vegetation with the annual rainfall of 2167 mm.

Field observation was conducted in January 2008 following the Soil Survey Manual (Soil Survey Division Staff 1993) and the pedons were classified using Soil Taxonomy (Soil Survey Staff 2006). As many as 15 soil samples (5 samples from each pedon) were taken from the field based on the depth of soil horizon. The soil samples were analyzed for their mineral composition, physical and chemical properties.

Total sand mineral fraction was analyzed using polarization microscope with line counting method, while clay mineral was by x-ray diffractometry after saturation by Mg⁺, Mg⁺ glycerol, K⁺, and K⁺ then heating to 550°C. Physical and chemical analyses included texture with pipette methods, pH (H₂O) with glass electrode, organic-C (acid dichromate digestion), total N (Kjeldahl digestion), exchangeable bases and CEC using NH₄O-acetate pH 7.0 extraction, exchangeable Al (by 1N KCl extraction), P₂O₅ and K₂O (by 25% HCl extraction), P retention (Blackmore *et al.* 1981), and amorphous Fe and Al (by ammonium oxalate extraction). The soil analyses were conducted following the standard procedures of the Soil Laboratory of the Indonesian Center for Agricultural Land Resources Research and Development, Bogor, Indonesia, most of which were also described in Soil Survey Laboratory Staff (1991).

RESULTS AND DISCUSSION

Morphological Characteristics

In the field, it was easy to recognize morphological characteristics of Spodosols by coarse texture (sand or loamy sand), the presence of E albic horizon with pale or light color under dark and organic matter rich A horizon, and dark B spodic horizon under bleached E albic horizon.

Some morphological properties of the three pedons investigated are given in Table 1. Horizon composi-

tion showed that there are two different parent materials between topsoil and subsoil, Oa-E-Bhs/x-2B/BC-2C. Numerical symbol of 2 in front of horizon symbol indicates the different materials between upper part which is volcanic sand material and the lower part which is liparite tuff.

Compared with Spodosols from lowland area in East Kalimantan as reported by Prasetyo *et al.* (2006), the Spodosols from Toba highland (Fig. 1) had thinner E and B horizons, 5-12 cm vs 32-80 cm in the E horizon, and 18-28 cm vs 30-110 cm in the B horizon. Also the depth of B spodic horizon of Toba Spodosols was shallower, (22-23 cm) than the East Kalimantan ones (50-97 cm).

From the soils investigated, UG 979 had advanced soil development compared to JH 622 and KR 1268. The thickness of E albic and B spodic horizons in the UG 979 (12 and 28 cm thick), compared to E albic and B spodic horizons in JH 622 (5 and 18 cm thick) and KR 1268 (9 and 19 cm thick) and the presence of duripan in UG 979 and fragipan in JH 622 and KR 1268, indicated that UG 979 was more developed than the others. The levels of soil development among the three pedons were UG 979, KR 1268, and JH 622.

The Spodosols from Toba highland had a higher content of weatherable mineral than those from East Kalimantan (Prasetyo *et al.* 2006). According to Buurman (1986), the less the amount of cation or the poorer the parent material, the deeper is the B spodic horizon. The kind of parent materials not only influence the depth of B spodic horizon, but also the

thickness of E albic horizon. The poorer soil parent material, the thicker is the E albic horizon. Some other factors that enable the formation of thick E albic horizon are flat relief covered by vegetation, coarse texture and loose structure, low bases, absence of weatherable iron mineral, and vegetation that are tolerant to intensive podzolisation with high rainfall

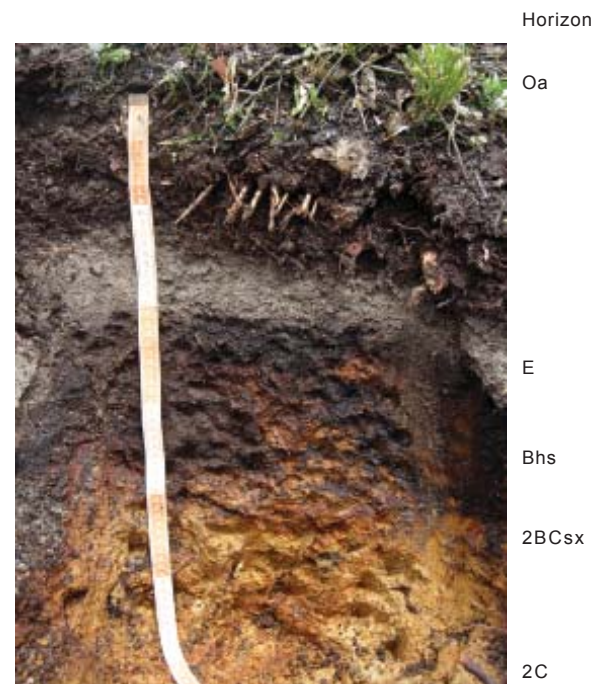


Fig 1. Spodosols of Toba highland derived from volcanic sand over liparite tuffs.

Table 1. Selected morphological characteristics of Spodosols in Toba highland, North Sumatra.

Horizon	Depth (cm)	Soil color (moist)	Texture	Structure and consistency
Pedon JH 622; slope 6%; 1710 m elevation (98°37'44" East Longitude and 2°25'14" North Latitude)				
Oa	0-14	Reddish dark brown (5YR3/2)	Sapric materials	Massive, non-sticky
E	14-23	Light gray (2.5Y7/2)	Sand	Loose, single grain
Bhx	23-41	Very dark brown (10YR2/2)	Sandy loam	Massive, firm, non-sticky
2Bw	41-57	Yellowish red (5YR4/6)	Sandy loam	Massive, firm, non-sticky
2C	57-77	Yellow (10YR7/8)	Sandy clay	Massive, firm, non-sticky
Pedon KR 1268; slope 6%; 1676 m elevation (98°37'19" East Longitude and 2°24'34" North Latitude)				
Oa	0-17	Black (7.5YR2,5/1)	Sapric materials	Massive, non-sticky
E	17-22	Pinkish gray (7.5YR6/2)	Sand	Loose, single grain
Bhs	22-26	Black (10YR2/1)	Sandy loam	Massive, very friable
2BCsx	26-41	Very dark brown (7.5YR2,5/3)	Clay loam	Massive, very firm
2C	41-68	Yellow (5Y7/6)	Sandy clay loam	Massive, firm, slightly sticky
Pedon UG 979; slope 6%; 1821 m elevation (98°37'15" East Longitude and 2°27'27" North Latitude)				
Oa	0-10	Very dusky red (5R2.5/2)	Sapric materials	Massive, non-sticky
E	10-22	Brownish light gray (10YR6/2)	Loamy sand	Loose, single grain
Bhs	22-36	Grayish very dark brown (10YR3/2)	Sandy clay loam	Massive, firm, slightly sticky
2Bhsx	36-50	Reddish dark brown (5YR3/4)	Sandy clay loam	Massive, firm, slightly sticky
2BC	50-75	Yellowish dark brown (10YR4/4)	Sandy clay loam	Massive, slightly sticky

(Mc. Keague *et al.* 1983). The thickness or depth of E albic horizon will depend on sesquioxide content of the parent material (Mohr *et al.* 1972).

The existence of hard horizon in the JH 622 and KR 1268 can be classified as fragipan, while on UG 979 the layer is harder and is not broken by water and classified as duripan. The fragipan is in 22-23 cm depth and duripan is in 36 cm depth. Fragipan from East Kalimantan Spodosols was found in 50 cm depth.

The surface horizon of all pedons investigated had very dark red, reddish dark brown to black colors. The dark colors show at the presence of high organic matter content in those layers caused by impeded litter decomposition and accumulation of organic matter due to decreasing temperature with high rainfall (Buurman 1984).

The soil in the E albic horizon was characterized by high value (6-7) and low chroma (1-2), indicating that eluviation process occurred. From the three pedons investigated, the colors of E albic horizon ranged from pink gray, gray, to brownish light gray. The B spodic horizon had darker color as caused by high organic matter content. The value and chroma of spodic horizon were generally less than 3. The colors of B spodic horizons varied from very dark brown, reddish dark brown, grayish very dark brown, and black.

Soil structure in the Oa horizon was massive and non-sticky, while the E albic horizon was loose and

single grains. B spodic horizon had a massive structure with firm to very firm consistency, while C horizon had massive and compact structure.

Physical and Chemical Properties

Some physical and chemical properties of Spodosols from Toba highland were given in Table 2 and 3. Grain size distribution was dominated by sand fraction, varying from 47% to 86% in the topsoil or Oa horizon, from 66% to 94% in the E albic horizon, and from 62 to 95% in the B spodic horizon. The sand fraction from liparite tuff (2Bw, 2BC, and 2C horizons) was very high, i.e., 81-91%. Silt and clay fractions on some horizons could not be separated by pipette methods, so some data in Table 2 are the sum of silt and clay fractions. From the available data, the clay fraction was generally less than 5%, while silt fraction ranged, between 3% and 28%.

Soil pH tended to increase with soil depth, ranging from 3.7 to 5.3 or very acid to acid. The lowest soil pH was in the surface layer (Oa horizon), ranging from 3.7 to 4.3, increased to E albic and B spodic horizons ranging from 4.4 to 5.0. The low soil pH in the surface horizon is caused by organic layer with sapric material. This condition was somewhat different from East Kalimantan Spodosols (Prasetyo *et al.* 2006) that the lowest soil reaction was found in B spodic horizon.

Table 2. Texture, C-organic, C/N ratio, and pH (H₂O) of Spodosols in Toba highland, North Sumatra.

Horizon	Depth (cm)	Texture (%)			C (%)	C/N	pH (H ₂ O)
		Sand	Silt	Clay			
Pedon JH 622; slope 6%; 1710 m elevation (98°37'44" East Longitude and 2°25'14" North Latitude)							
Oa	0-14	47	53*		37.66	80	3.9
E	14-23	66	33	1	4.04	40	4.8
Bhx	23-41	86	14		17.26	91	5.0
2Bw	41-57	91	9		5.80	59	4.8
2C	57-77	84	16		1.44	53	4.9
Pedon KR 1268; slope 6%; 1676 m elevation (98°37'19" East Longitude and 2°24'34" North Latitude)							
Oa	0-17	86	11	5	19.69	16	4.3
E	17-22	94	5	1	1.45	23	5.0
Bhs	22-26	95	3	2	9.71	76	4.4
2BCsx	26-41	82	18*		2.02	31	4.8
2C	41-68	81	19		1.02	25	5.3
Pedon UG 979; slope 6%; 1821 m elevation (98°37'15" East Longitude and 2°27'27" North Latitude)							
Oa	0-10	47	53*		35.37	16	3.7
E	10-22	84	14	2	2.10	31	4.7
Bhs	22-36	62	28	10	5.67	37	4.6
2Bhsx	36-50	83	17		10.75	67	4.8
2BC	50-75	85	15		3.58	62	5.2

* = not dispersed (sum of silt and clay).

Table 3. Exchangeable bases, CEC, base saturation, and aluminum saturation of Spodosols in Toba highland, North Sumatra.

Horizon	Depth (cm)	Exchangeable bases (NH ₄ OAc - pH 7.0)				Sum of bases	Soil CEC	Base saturation (%)	Al (KCl 1N) cmolc kg ⁻¹	Al saturation (%)
		Ca	Mg	K	Na					
Pedon JH 622; slope 6%; 1710 m elevation (98°37'44" East Longitude and 2°25'14" North Latitude)										
Oa	0-14	0.55	0.11	0.42	0.06	1.14	50.84	2	1.68	60
E	14-23	0.12	0.02	0.04	0.06	0.24	0.72	32	0.00	0
Bhx	23-41	0.06	0.02	0.11	0.06	0.25	41.34	1	2.29	90
2Bw	41-57	0.06	0.01	0.04	0.05	0.16	17.89	1	0.43	73
2C	57-77	0.06	0.01	0.04	0.06	0.17	7.49	2	0.00	0
Pedon KR 1268; slope 6%; 1676 m elevation (98°37'19" East Longitude and 2°24'34" North Latitude)										
Oa	0-17	0.30	0.32	0.44	0.08	1.14	28.41	4	0.00	0
E	17-22	0.07	0.05	0.03	0.05	0.20	0.21	91	0.00	0
Bhs	22-26	0.04	0.02	0.04	0.03	0.13	15.33	1	2.77	96
2BCsx	26-41	0.05	0.01	0.02	0.04	0.12	7.60	2	0.00	0
2C	41-68	0.04	0.01	0.10	0.05	0.20	7.91	3	0.00	0
Pedon UG 979; slope 6%; 1821 m elevation (98°37'15" East Longitude and 2°27'27" North Latitude)										
Oa	0-10	0.26	0.18	0.38	0.06	0.88	68.42	1	3.24	79
E	10-22	0.04	0.01	0.02	0.03	0.10	0.94	12	0.10	46
Bhs	22-36	0.02	0.02	0.02	0.04	0.10	12.51	1	3.34	97
2Bhsx	36-50	0.04	0.01	0.01	0.03	0.09	25.92	1	2.40	97
2BC	50-75	0.08	0.01	0.02	0.04	0.15	5.43	3	0.11	41

Organic matter content varied within the pedons investigated (Fig. 2). The highest content was found in Oa horizon, decreased in E albic horizon, increased in B spodic horizon, and decreased again in Bw, BC or C horizons. The organic matter content in the Oa horizon ranged between 19.69% and 37.66%. In the eluviation horizon which constitutes the leaching layer, the organic matter content remained relatively high, ranging between 1.45% to 4.04% (Table 2). Buurman *et al.* (1994) postulates that the C/Fe ratios increase with increasing soil development. In the iluviation or accumulation horizon, the organic matter content increased compared to the eluviation horizon, ranging between 5.67% to 17.26%, while in the C horizon the organic matter content decreased in the range of 1.02-3.58%. Distribution of organic matter content by soil depth showed that accumulation of organic matter occurred in the surface layer, decreased to E albic horizon by leaching, and increased to B spodic horizon by accumulation.

C/N ratio showed a very large variation, in the range of 16-80 in the surface layer, 23-40 in the E albic horizon, and 37-91 in the B spodic horizon. That condition is comparable with the Spodosols from East Kalimantan (Prasetyo *et al.* 2006). The different C/N ratios among pedons investigated could be caused by the difference in their decomposition level, kind of organic matter, and environmental condition.

The movement of organic matter to the lower horizon is in the complex form with Al, and with or without Fe (Buurman and Jongmans 2002). The decrease of Al content in the E albic horizon was caused by eluviation process, and the increase of Al in the B spodic horizon was caused by iluviation. In the B spodic horizon, exchangeable Al ranged between 2.29 and 3.34 cmolc kg⁻¹, while in the E albic horizon was < 0.1 cmolc kg⁻¹. The same condition also occurs in the Fe extractable by ammonium oxalate which tended to be higher in the Bhs/Bhx horizon compared to that in the E albic horizon.

P₂O₅ and K₂O contents showed an enrichment in the surface layer, decreased in E albic horizon, and increased in B spodic and C horizons (Fig. 2). The absolute value of K₂O was higher compared to that of P₂O₅. The high values of both K₂O and P₂O₅ in the surface layer (Oa horizon) apparently occur as enrichment process (biological cycle) through various nutrients by forest plantation roots from the soil, and then return to the surface or near surface soil through leaves or plantation branch as a litter (Quideau *et al.* 1999).

Relationships between P₂O₅ and organic-C (Fig. 3) showed that the highest correlation was in the JH 622 (R²= 0.969), followed by KR 1268 (R²= 0.7615) and UG 979 (R²= 0.6447). This indicates that the more developed the soil is, the less relationship between

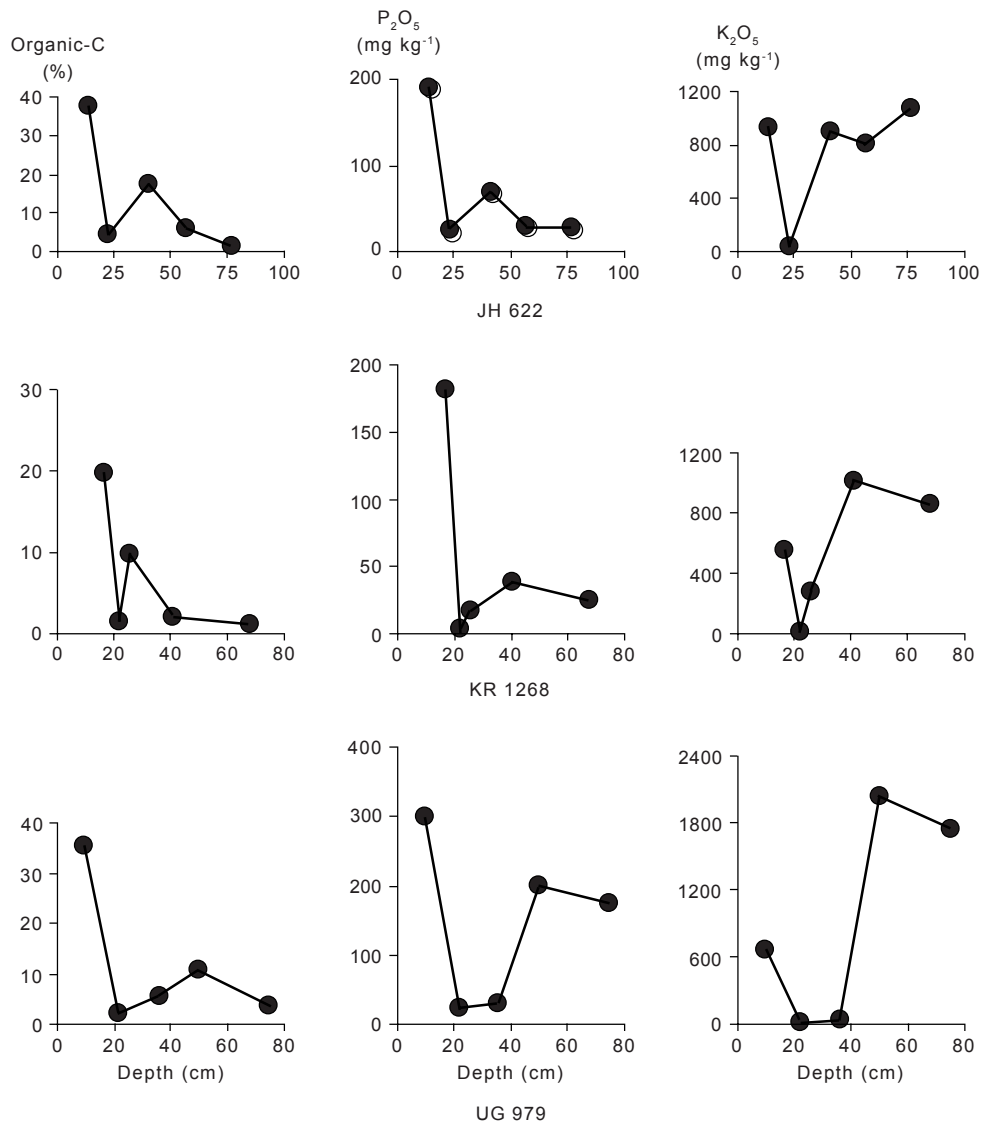


Fig. 2. Distribution of organic-C, P_2O_5 and K_2O with soil depths of Spodosols in Toba highland, North Sumatra.

P_2O_5 and organic-C. In this case, some P may already take up by plant.

In the eluviation horizon, both P_2O_5 and K_2O contents drastically decreased, related with leaching process in the horizon. On the contrary in the B spodic or accumulation horizon, both P_2O_5 and K_2O contents increased. The high content of K_2O in the pedons investigated (2B and 2C horizons) came from liparite tuff containing biotite and sanidine.

Exchangeable cations (Ca, Mg, K, and Na) were very low in all pedons investigated (Table 3). High rainfall (2167 mm year⁻¹) and coarse texture of the soil were important agents for leaching of bases. Nevertheless, exchangeable bases in the surface layer were 2-20 times higher compared to that in the lower horizon. Like P_2O_5 and K_2O , the high content of exchangeable

bases in the surface layer was caused by biological cycle of forest soil (Suharta and Prasetyo 2008).

Cation exchange capacity (CEC) varied from 0.21 to 68.42 cmol_c kg⁻¹. The lowest CEC was in the E albic horizon and the highest CEC was in the surface and B spodic horizons that were rich in organic matter. There were positive relationships between CEC and organic-C (Fig. 4) with R^2 of 0.83, 0.93 and 0.98 for JH 622, KR 1268 and UG 979, respectively. The positive relationships between organic-C and soil CEC also showed by Prasetyo *et al.* (2009) in the soil derived from pyroclastic material in Toba highland.

Base saturation was very low (<5%) for all pedons, indicating that intensive leaching of bases has occurred. In every pedon, base saturation in E albic horizon had the highest value, due to the very low

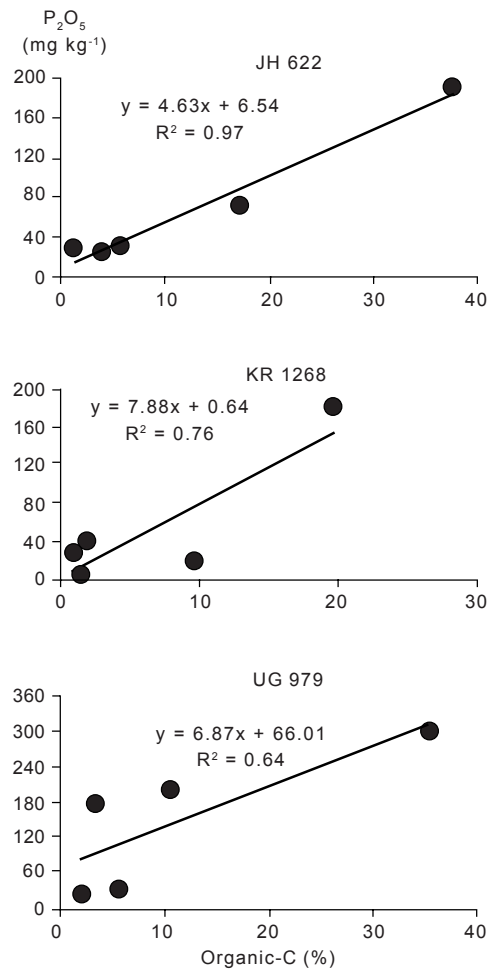


Fig 3. Relationships between organic-C and P_2O_5 of Spodosols in Toba highland, North Sumatra.

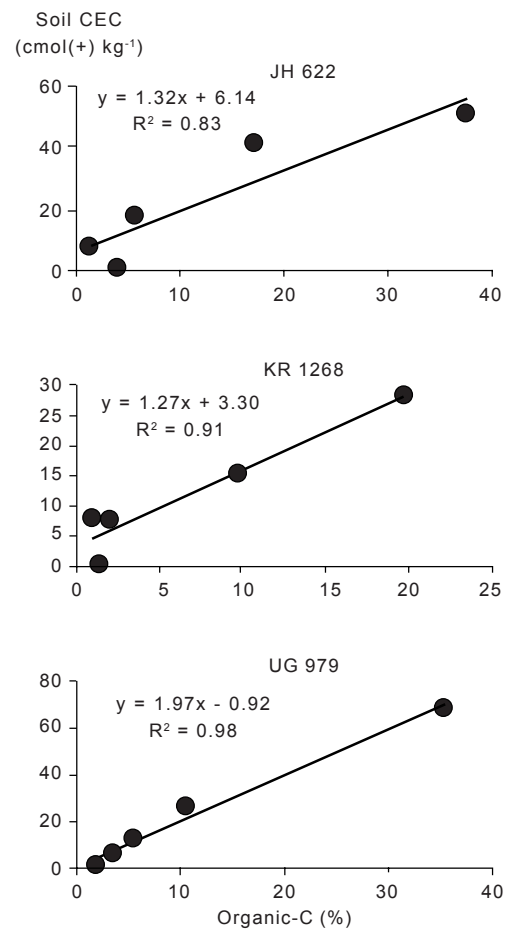


Fig 4. Relationships between organic-C with soil CEC in the pedons of Spodosols in Toba highland, North Sumatra.

CEC. The highest Al saturation occurred in the surface layer (Oa) and B spodic horizon. Apparently the Al came from organic-Al complex. The relatively higher Al saturation in the UG 979 compared to that of other pedons may be caused by more develop stage of UG 979 than JH 622 and KR 1268 formation.

Andic Soil Properties

The andic soil properties were resulting from the presence of several minerals such as allophane, imogollite, ferrihydrite, or Al-humus complex in the soil. These minerals are also recognized as amorphous materials resulted from weathering of volcanic material with high content of volcanic glass. According to Soil Survey Staff (2006), soils with andic properties should not have organic carbon more than 25% (by weight) and meet one or both of the following requirements:

- Al + 1/2 Fe percentages (by ammonium oxalate) totaling 2.0% or more, bulk density 0.9 g cm⁻³ or less, P retention 85% or more, *or*
- P retention $\geq 25\%$, Al + 1/2 Fe percentages (by ammonium oxalate) totaling 0.4% or more, a volcanic glass content 5% or more, and
- Al + 1/2 Fe percentages (by ammonium oxalate) times (15.625 + volcanic glass content, percent) ≥ 36.25 .

Results from soil analyses indicated that the soil P retention ranged from 38% to 85%, Al + 1/2 Fe percentages (by ammonium oxalate) 0.65-12.83, and Al + 1/2 Fe percentages (by ammonium oxalate) times (15.625 + volcanic glass content, percent) 14.16-203.39 (Table 4), and volcanic glass content from sand fraction ranged from 6% to 25% (Table 5). Based on these conditions, all pedons investigated can be categorized as those of andic soil.

The existence of covering volcanic sandy materials over liparite tuff was clearly identified from the amount

Table 4. P-retention, Al, and Fe (by NH₄-oxalate) of Spodosols in Toba highland, North Sumatra.

Horizon	Depth (cm)	P-retention (%)	NH ₄ -oxalate %Al+1/2Fe (%)	(%Al+1/2Fe)*15.625+ % volc.glass > 36.25 (%)
Pedon JH.622; slope 6%; 1710 m elevation (98°37'44" East Longitude and 2°25'14" North Latitude)				
Oa	0-14	13	0.51	22.05
E	14-23	1	0.05	21.70
Bhx	23-41	85	6.81	112.41
2Bw	41-57	79	11.81	188.61
2C	57-77	71	10.10	161.81
Pedon KR.1268; slope 6%; 1676 m elevation (98°37'19" East Longitude and 2°24'34" North Latitude)				
Oa	0-14	2	0.15	4.34
E	14-23	< 1	0.07	26.17
Bhs	23-41	58	2.08	45.58
2BCsx	41-57	82	12.83	203.39
2C	57-77	90	13.04	206.75
Pedon UG.979; slope 6%; 1821 m elevation (98°37'15" East Longitude and 2°27'27" North Latitude)				
Oa	0-14	9	0.38	28.94
E	14-23	2	0.04	24.05
Bhs	23-41	38	0.65	14.16
2Bhsx	41-57	84	7.93	127.98
2BC	57-77	77	9.09	146.03

Table 5. Clay and sand mineral composition of Spodosols in Toba highland, North Sumatra.

Mineral composition	Pedon										
	JH 622				KR 1268				UG 979		
	I	II	III	IV	I	II	III	IV	II	III	IV
Clay fraction											
Amorphous minerals		++++		++++	++++		++++		++++		
Kaolinite					(+)				(+)		
Sand fraction											
Opaque	9	1	1	1	5	3	5	1	12	5	4
Zircon	tr	tr	1	tr	tr	5	3	tr	6	10	1
Turbid quartz	5	2	1	tr	tr	5	3	tr	6	10	1
Transparance quartz	23	51	29	30	13	33	34	16	34	32	22
Weathered minerals	tr	-	7	1	tr	tr	tr	tr	-	tr	20
Rock fragment	2	tr	1	tr	1	tr	1	tr	2	1	2
Volcanic glass	14	21	6	4	2	25	13	3	23	24	1
Oligoclase	tr	1	1	1	tr	2	1	1	tr	tr	tr
Andesine	tr	2	1	2	1	tr	1	1	tr	-	tr
Labradorite	tr	1	1	tr	tr	-	tr	tr	-	-	-
Orthoclase	-	-	-	-	tr	-	-	tr	tr	-	tr
Sanidine	3	21	10	7	4	30	21	9	20	14	20
Biotite	tr	-	39	50	65	1	19	68	tr	-	20
Green hornblende	4	tr	1	2	4	tr	2	1	tr	tr	7
Augite	6	-	tr	tr	tr	-	-	-	-	-	-
Hyperstene	27	tr	tr	1	2	-	-	tr	-	tr	1
Tourmaline	tr	tr	-	tr	tr	tr	tr	tr	-	tr	tr
Enstatite	7	tr	1	1	2	tr	tr	tr	tr	tr	1
Weatherable minerals	63	46	61	68	81	59	58	83	45	39	52

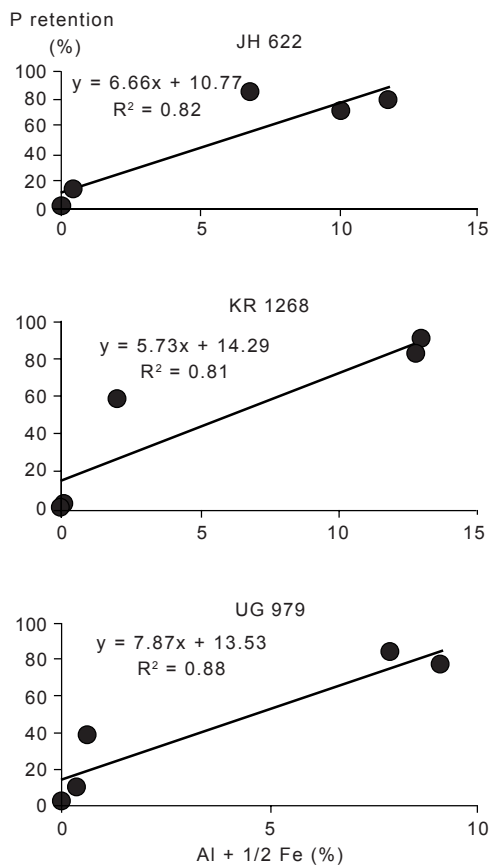


Fig. 5. Relationships between P retention and amorphous material in the form of Al + 1/2 Fe percentages (by ammonium oxalate) of Spodosols in Toba highland, North Sumatra.

of amorphous materials in the form of Al + 1/2 Fe percentages (by ammonium oxalate), that increased at 2Bw and 2C horizons (JH 622), 2BCsx and 2C horizons (KR 1268), and 2Bhsx and 2BC horizons (UG 979) with values consecutively of 11.81% and 10.10%, 12.83% and 13.04%, 7.93% and 9.09%. P retention of Spodosols investigated was positively influenced by amorphous materials in the form of Al + 1/2 Fe percentages extracted by ammonium oxalate (Fig. 5).

Composition of Sand and Clay Minerals

Sand mineral composition was dominated by quartz, volcanic glass, sanidine, and biotite. The other sand minerals like opaque, zircon, rock fragment, weathered mineral, oligoclase, andesine, labradorite, green amphibole, augite, hyperstene, and enstatite also present in a lesser amount (Table 5).

These mineral compositions indicate that soil parent materials are derived from liparite tuff. One of

the main soil characteristics from liparite tuff of Toba highland is the presence of sanidine and biotite. The sand mineral composition of Spodosols in Toba highland was different from Spodosols from lowland areas which are dominated by quartz (Suharta and Suratman 2004; Prasetyo *et al.* 2006). Although in Spodosols from Toba highland fragipan and duripan were already formed, the soils were still in the early development stage.

X-RD analysis showed that the crystalline clay minerals such as kaolinite were only found in the surface layer (Oa) as indicated by small peak of 7.16 Å and 3.56 Å, quartz indicated by 4.26 Å and 3.34 Å, and cristobalite indicated by 4.04 Å (Fig. 6). Actually quartz is originated from very fine sand fraction that mixed into clay fraction. Dome-shape diffractogram indicated that amorphous clay minerals were found both in the surface layer (Oa) and sub-surface layer (Bhs) of Spodosols from Toba highland. The presence of amorphous mineral in B spodic horizons was also reported by Buurman and Jongmans (2002). This result was totally different with other Spodosols from East Kalimantan that contained kaolinite, illite, and vermiculite in their eluviation horizon (Prasetyo *et al.* 2006).

Soil Classification

All pedons investigated were characterized by spodic subsurface diagnostic horizons, the presence of fragipan and duripan, and also andic soil properties. Grain size distribution in the surface layer, based on field observation, was sand, while in the subsurface layer was medial. Clay mineral composition was dominated by amorphous mineral. The effective soil depth was shallow due to the presence of duripan, fragipan, and densic properties of C horizon. Soil temperature regime was isothermic. Based on their horizon characteristics, all pedons could be classified based on Soil Taxonomy (Soil Survey Staff 2006) as follow:

JH 622. This pedon had spodic horizon with > 6% organic carbon content, a fragipan, and andic soil properties, so in the subgroup level it was classified as Andic Fragihumods. In the family level, the soil was classified as sandy over medial, siliceous over amorphic, shallow, isothermic, Andic Fragihumods.

KR 1268. This pedon had spodic horizon with > 6% organic carbon content, but the thickness of this horizon was < 10 cm, a fragipan, and andic soil properties, so in the subgroup level it was classified

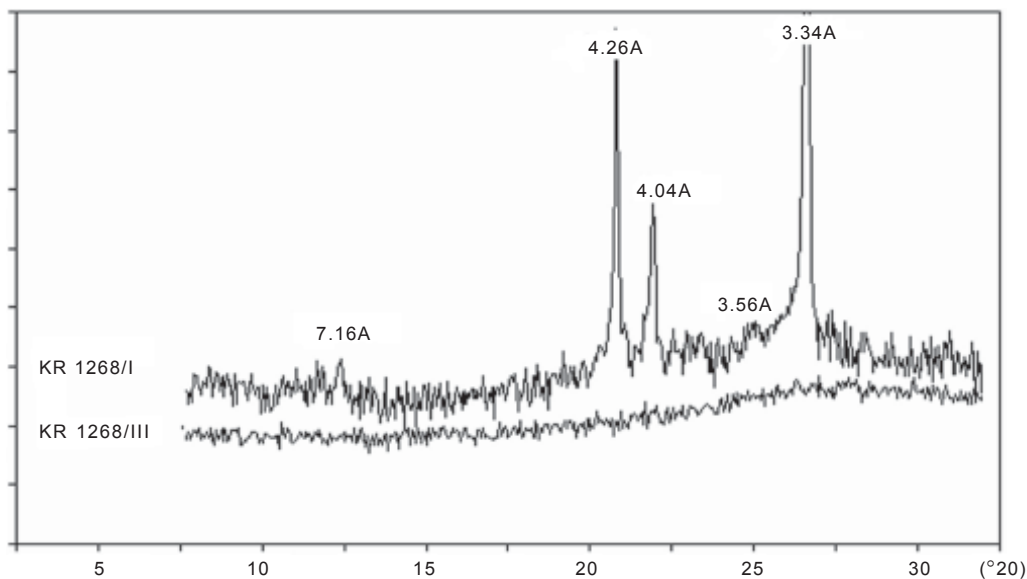


Fig. 6. X-ray diffractogram from Oa and Bhs horizons of KR 1268 (saturated with Mg^{++}) of Spodosols in Toba highland, North Sumatra.

as Andic Fragiorthods. In the family level, the soil was classified as sandy over medial, siliceous over amorphous, shallow, isothermic, Andic Fragiorthods.

UG 979. This pedon had spodic horizon with > 6% organic carbon content, a duripan, and andic soil properties, so in the subgroup level it was classified as Andic Durihumods. In the family level, the soil was classified as sandy over medial, siliceous over amorphous, shallow, isothermic, Andic Durihumods.

Characteristics and Utilization of Spodosols in Toba Highland

Spodosols in Toba highland were characterized by coarse texture. The surface organic layers varied in their thickness. It was formed as a result of impeded litter decomposition process. The soil horizon composition showed a clear differentiation among surface horizon (Oa), E albic horizon, B spodic horizon, and C horizon. The thickness of albic and spodic horizons were classified as thin and shallow. These conditions are agreeable with Buurman (1986) who stated that in Spodosols derived from parent material rich in weatherable mineral, the immobilization of Al complex and Fe with organic matter occurs in the shallow soil depth.

Chemical soil properties were characterized by very high organic matter content, except in E albic horizon.

K_2O content was very high due to biotite and sanidine contents in the soil. P_2O_5 was low to moderate, and bases were very low. In the eluviation horizon (5-12 cm thick), the P_2O_5 , K_2O and organic carbon contents were very low.

P retention varied from very low to very high. The highest P retention was found in B spodic and C horizons which were rich in amorphous material. Bh or Bhs horizons which were rich in organic carbon fixed higher P than Bs or Bsh (Arbestain *et al.* 2002), due to higher Al and Fe extractable by ammonium oxalate.

The weatherable minerals in sand fraction from which nutrients are derived, were high. The weatherable minerals such as pyroxene-amphibole (hyperstene, augite, enstatite and hornblende), mica (biotite), K-feldspar (sanidine, orthoclase) and Ca-Na feldspar (oligoclase, andesine, labradorite) are sources of Mg, Ca, Fe, K, and Na nutrients. Despite the high weatherable minerals, however, the exchangeable bases and base saturation of the soils were very low due to intensive leaching processes as caused by low nutrient holding capacity of the soils. P loss in the sandy soils is one of the main problems. Adding organic matter including biosolid is expected to reduce the loss of P through leaching process because of conversion of soluble P to organic-P to form organic-Al(OH) $^{2+}$ as well as Fe-organic complexes. Thus if the land is bare, the mineralization process in the sandy soil will accelerate. Intensive fertilization may cause a

reduction of the environmental quality, especially water quality (Yang *et al.* 2008)

Utilizing Spodosols for agriculture entails several constraints such as low fertility, coarse texture and low water and nutrient retention, and shallow effective soil depth. Intensive leaching under intensive soil management may risk the environment. Thus these soils should be conserved as forest as their development poses high cost on soil care (Yaloon 1996) and environmental risks.

CONCLUSION

Spodosols in Toba highland were derived from volcanic sand over liparite tuff. Both materials had similar mineral composition, but different in their amorphous mineral contents. Based on their soil development, these Spodosols were in the early soil development stage, characterized by high content of weatherable minerals and domination of amorphous minerals.

These Spodosols were shallow, had organic matter layer (Oa) and E albic and B spodic horizons. The thickness of each horizon was thin, ranging from 10 to 17 cm for Oa organic matter horizons, 5-12 cm for E albic horizons, and 12-28 cm for B spodic horizons. Although the weatherable mineral contents were high, the bases and nutrients were very low, indicating that leaching process was very intensive.

The sandy Spodosols with loose soil structure in the mountainous area of Toba highland are very prone to erosion, especially after land clearing. To protect the environment, forests with Spodosols are not recommended for agricultural purposes, rather they should be protected as forest.

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