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Weathering Behaviour of a Basaltic Regolith from Pahang, Malaysia

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ABSTRAK

Ciri-ciri dan kadar luluhawa pada regolit saprolit dalam terluluhawa yang terbentuk daripada batuan basalt telah dikaji. Jujukan regolit tanah-saprolit-batu sedalam 15 m yang terletak di bahu jalan di Pahang, Malaysia, telah dipilih untuk tujuan ini. Kadar luluhawa pada regolit ini telah dinilai dengan beberapa indisis luluhawa, perubahan pada sifat kimia-fizik tanah, mineralogi lempung dan ciri-ciri mikrofabrik. Kesemua nilaian telah membuktikan bahawa kadar luluhawa adalah tinggi dan cepat, walaupun di peringkat pembentukan saprock. Kehilangan keterlaluan elemen utama seperti K, Na, Ca, dan Mg, dan penambahan jelas oleh Fe, Ti, Cu dan Nb berlaku semasa proses saprolitizasi, mungkin menjelaskan bentuk luluhawa yang tinggi pada regolit tanah ini.

ABSTRACT

The characteristics and degree of weathering in a deep saprolitic regolith developed on basalt were investigated. A 15 m deep regolith of soil-saprolite-rock sequence, located along a new road cut in Pahang, Malaysia, was selected. The intensity of weathering in this regolith was assessed by various weathering indices, as well as by the changes in the physico-chemical properties, clay mineralogy and the microfabric characteristics of the profile. All assessments gave strong evidences of intense weathering, even at the stage of saprock formation. Extreme depletion of major elements such as K, Na, Ca and Mg, and significant enrichment of Fe, Ti, Cu and Nb occurred during saprolitization process, and, these perhaps explain the extreme weathering pattern of this regolith.

INTRODUCTION

The extent to which particular elements are mobilized during weathering depends upon the control of solubility in aqueous solutions and their interaction between these solutions and the complex surfaces of primary and secondary minerals. Thornber (1992) reported that cations were more mobile at low pH while anions were mobile at higher pH.

Weathering and mineral transformation are important phenomena in the arena of the Malaysian soils. Roe (1951) first reported the observations of weathering profiles in Peninsular Malaysia. An intensive study on soil formation and its variation with altitude throughout the peninsula was investigated by Burnham (1978). Eswaran and Wong (1978) and Yeow (1975), made some detailed studies on the chemical, mineralogical and micromorphological changes related to the transformation of parent rocks to soils in granite. Study on metamorphic rocks was conducted by Stoops *et al.* (1990), and Zauyah (1986). The genesis of basaltic soils was reported by Ives (1966), and West and Dumbleton (1970), who concluded that the basaltic rocks were formed probably during the middle Eocene age.

The present basalt regolith studied was composed of the soil-transition zone-saprolite-rock sequence. The saprolite, that is the weathered rock, comprised the largest portion of the regolith, and is increasingly important to the Malaysian upland plantation industry. The unavoidable terracing during crop planting and road construction activities, landslides and erosion had exposed these materials to or near the surface and become accessible to roots. This paper describes the degree of weathering and changes in the regolith characteristics under the humid tropical, well drained conditions of Peninsular Malaysia.

MATERIALS AND METHODS

Location and Geological Setting

The selected regolith developed on basalt is located in Pahang state on the West coast of Peninsular Malaysia. The geological study by Hutchison (1973), suggested that the extrusion of basaltic lava occurred during the Quaternary age and it overlies and surrounds the granitic hills to the north and northwest of Kuantan town. The rock is compact, microcrystalline, and greenish black vesicular olivine basalt. The climate is equatorial with an annual precipitation of 3660 mm and potential evapotranspiration of 1,130 mm. The soil moisture regime is udic and the soil temperature regime is isohyperthermic with the mean annual soil temperature of 28.7 ^{0}C. The landscape is gently undulating and the profile was sampled on a new road along the road from Kuantan to Sungai Lembing, about 8 km from Kuantan town. A profile of about 15 m deep (*Fig. 1*) was horizonated and morphologically described following the criteria of the USDA (1981). The profile is classified as fine, clayey, kaolinitic, isohyperthermic, typic Acrudox (Soil Taxonomy 1996). Bulk samples and undisturbed samples of soil, saprolite and rock were taken for various analysis.

Laboratory Analysis

The bulk samples were air-dried and were passed through a 2 mm sieve. The undisturbed core samples were taken for the bulk density determination. The pipette method was employed to estimate the soil texture and the water dispersible clay (WDC) was determined by successive sedimentation method (Tessens 1984). Soil pH was measured in suspension of 1:2.5 soil:solution ratio, while pH in sodium fluoride was estimated after stirring vigorously for two minutes (Rayment and Higginson 1992). The method proposed by Ferrari and Megaldi (1983) was used to determine the soil abrasion pH. All pH readings were recorded using a glass electrode pH meter. Soil organic carbon was determined by the Walkley-Black dichromate titration method and nitrogen by macro-kjedahl digestion procedure (Bremner and Mullraney

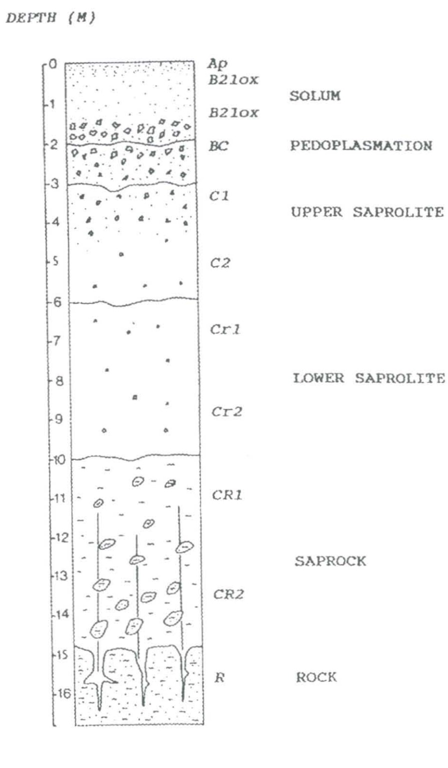

Fig. 1: A schematic sketch of a basalt profile

1982). The free Fe content was extracted by dithionite-citrate-bicarbonate method of Mehra and Jackson (1960). For the CEC and exchangeable bases determination, the leaching method with 1M ammonium acetate buffered at pH 7 was used. The determination of aluminium and P sorption index were done following the aluminon method (Hsu 1963) and Bache and Williams (1971), respectively. The bulk mineralogy of the clay fraction of the soils and saprolites were analyzed by x-ray diffraction. Soil charge characterization was determined by potentiometric titrations and ion retention methods (Uehara and Gillman 1981).

Undisturbed samples from major horizons were collected in Kubiena boxes of 55 x 75 x 50 mm size. These samples were air-dried and impregnated with resin (araldite). Thin sections were prepared and described using the terminology outlined by Bullock *et al.*(1986). The major elemental chemical content of basalt rock and its weathering product were analyzed with the Inductively Coupled Plasma (ICP). An isovolumetric calculation was performed to determine the intensity of weathering through elemental mobility, converting the percentage weight chemical analysis to volume-based concentration by multiplying with the bulk density of the respective sample. Using the unweathered bedrock as the reference, absolute percentage gains and losses of each element were then calculated. The weathering indices of Parker (1970), Rock Alteration Index by Eswaran *et al.* (1973), and the Molar ratio and abrasion pH by Ferrari and Megaldi (1983), were adopted to evaluate the degree of weathering of this profile.

RESULTS AND DISCUSSION

Morphological Descriptions

A summary of the profile morphological descriptions is presented in Table 1. The profile is prominently characterized by clayey yellowish brown solum. The surface layers have a strong crumb that changes gradually to weak subangular blocky structure in the subsoil horizons. The consistency is friable and fluffy but becomes firm towards the upper saprolite layer. Drainage of the soil profile is somewhat excessive. The saprolitic layers are well weathered, yet massive, clayey, slightly friable but increase in firmness with depth, and become more coherent towards the rock. The upper saprolites are variegated in colors of mostly dark brown with reddish and grayish patches, but becomes more gray and greenish with depth towards the saprock. The drainage of the saprolite layers is somewhat imperfect.

Physico-Chemical Characterization

The selected physico-chemical properties of the profile are presented in Table 2. The profile is physically characterized by the high clay content throughout the regolith, with the content in the solum of > 70% while the saprolite of > 60%. The high clay content did not coincide with the very friable and fluffy consistency of the solum layers observed in the field, and this would suggest strong aggregation of clay by iron to form pseudosands and clayballs (Paramananthan 1977). Log clay percent (*Fig. 2*) roughly follows a straight line pattern in the saprolitic layers, suggesting that the presence of clay is most probably due to weathering (Eswaran and Wong 1978). This assumption is supported by the low

TABLE 1
Morphological characteristics of a basalt regolith

Horizon	Depth (m)	Texture	Color		Consistency	Structure
			Matrix	Mottles		
Soil	0 - 2	Clay	10YR4/4	nil	Friable-Fluffy	Crumb-SAB
Transition	2 - 3	Clay	10YR3/4	nil	Friable	SAB
Upper saprolite	3 - 6	Clay	2.5YR3/4	10YR4/1	Friable	Massive
Middle saprolite	6 - 10	Clay	2.5YR3/4	10YR4/1	Firm	Massive
Lower saprolite	10 - 15	Silty clay	2.5YR3/4	nil	Hard	Massive

TABLE 2
Selected physico-chemical characteristics of a basalt regolith

Horizon	Clay %	Log Clay %	B.D (g/cm^3)	WDC %	CEC	Exchangeable Bases (cmol (+)/kg soil)				PC	PDC	%O.C	%N	Fe_d % Index	P Sorption	Al	Soil pH		
						Ca	Mg	K	Na	(cmol(+)/kg clay)							pH_W	pH_{KCL}	ΔpH
Ap	78	1.9	0.98	33	6.2	0.87	0.59	0.28	0.11	2.5	23.0	2.60	0.27	12.4	78	0.01	5.34	4.79	-0.55
B2ox	80	1.9	1.09	0.4	2.2	0.30	0.05	0.09	0.05	1.0	20.1	0.86	0.13	12.5	82	0.01	4.81	4.52	-0.32
BC	66	1.8	1.37	0.4	1.1	0.26	0.05	0.05	0.05	0.8	23.1	0.06	0.02	14.9	82	0.01	5.14	5.44	0.30
Upper saprolite	64	1.8	1.17	0.3	2.9	0.29	0.04	0.09	0.03	1.3	22.8	0.02	0.01	12.5	82	0.04	4.84	4.47	-0.37
Middle saprolite	57	1.8	1.07	0.1	3.0	0.28	0.06	0.06	0.02	3.9	22.5	tr	tr	12.3	78	1.97	4.73	4.11	-0.62
Lower saprolite	30	1.5	1.17	0.1	5.7	0.27	0.09	0.06	0.02	15.7	45.4	tr	tr	12.5	71	3.64	4.61	3.92	-0.69
Rock	nd	nd	2.41	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd

Note: B.D - Bulk density, WDC - Water Dispersible Clay, CEC - Cation Exchange Capacity, PC - Permanent Charge, PDC - pH Dependent Charge, O.C - Organic carbon, N - Nitrogen, Fe_d - Dithionite extractable ferum, Al - Aluminium.

WDC values in these layers which range from 0.1 to 0.5%. The silt to clay ratio (*Fig. 2*) shows a curvilinear pattern with depth, being maximum at the lower saprolitic layer, and decreasing towards the solum. The decrease from the saprolitic layer towards the surface horizons points to the increase in weathering and soil formation (Van Wambeke 1962). The two phase curvilinear patterns as observed by Eswaran and Wong (1978) on a deep granitic profile were not detected in this profile, suggesting that this profile may experience extreme stage of weathering. This is supported by a drastic change in bulk density that occurs between the unweathered rock (2.41 g/cm^3) and the saprock layer (1.17 g/cm^3).

Intense rainfall and high temperature along the east coastal region of the peninsula resulted in a higher rate of organic matter decomposition and mineralization. The plot of log organic carbon shows a curvilinear distribution. The nick point appearing at 2.5 m corresponds to the separation of the pedological from saprolite layers (Singh and Singh 1987). The organic content is very low in the saprolite and could be attributed to its migration along fissures and remnants of cracks in the saprolite (Stone and Comerford 1994). The soil pH shows a decrease with depth, and could be attributed to the effect of organic matter content and degree of weathering. This is also supported by the drastic change in the abrasion pH values in Table 6. The DpH data indicates a positive value at the transition zone, suggesting the dominance of positive charge. Further study on the surface charge properties (Table 3) shows that values of the point of zero net charge (PZNC) are higher than the zero point of charge (ZPC or pH$_0$) values throughout the profiles, except for the surface horizon where the organic matter content

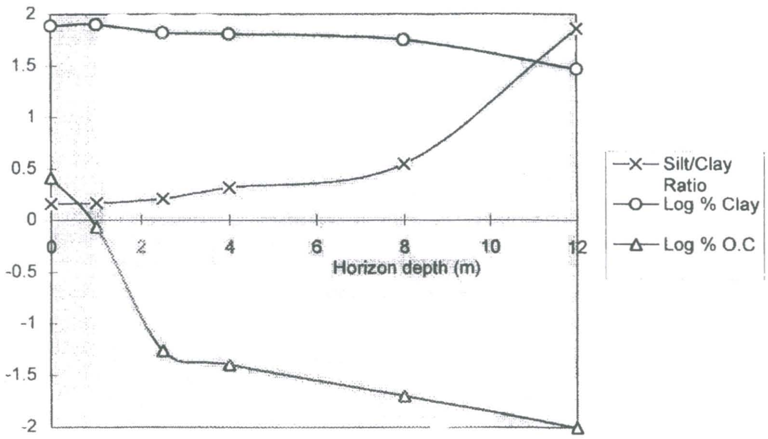

Fig. 2: Depth function or related soil properties

TABLE 3

Surface charge characteristics of a basalt regolith

Horizon	PZNC	ZPC (pH$_0$)	Negative Charge	Positive Charge	Net Charge
			(μmol(+)/g soil)		
Ap	3.71	4.17	-20.01	15.46	-4.54
B2ox	5.29	4.35	-13.57	15.71	2.14
Upper saprolite	5.85	3.91	-14.01	16.01	2.01
Middle saprolite	5.69	3.85	-13.14	16.45	3.31
Lower saprolite	3.74	3.65	-17.88	18.13	0.25

Note: PZNC - Point of zero net charge, PZC - Point of zero charge.

is higher. Similarly, the positive charge values were also found to be higher than the negative charge values at these horizons. The presence of positive charge indicates that the soil experiences extreme weathering stage (Tessens and Zauyah 1982; Van Wambeke 1992).

The PC and PDC values do not demonstrate increase with depth. The almost constant values may suggest little change in mineralogy as a result of intense weathering even at the lower saprolite layer. The CEC values are extremely low, except for the surface horizon where organic matter is abundant. The exchangeable bases for the whole regolith also point to a similar distribution pattern. In the east coastal areas of Peninsular Malaysia where rainfall and temperatures are high, weathering may reach great depth. Most of these bases may have already leached away even at the initial stage of saprolite formation (Burnham 1989).

Clay Mineralogy

Fig. 3 shows the results of the x-ray diffraction of the clay size fraction of the basalt profile. Only traces of primary minerals such as feldspar and olivine is detected in the saprolite layers. In the solum layers, strong peak for goethite and gibbsite are observed. The peak for gibbsite is weak in the saprolite layers, suggesting that most aluminium is well crystallized in soil materials. The low aluminium content in the soil as determined by aluminon method, may also point to a similar conclusion. Kaolinite peak is distinctively high in all horizons, suggesting that most weatherable minerals such as feldspar and olivine are well weathered into clay minerals, even at the lower saprolite layer.

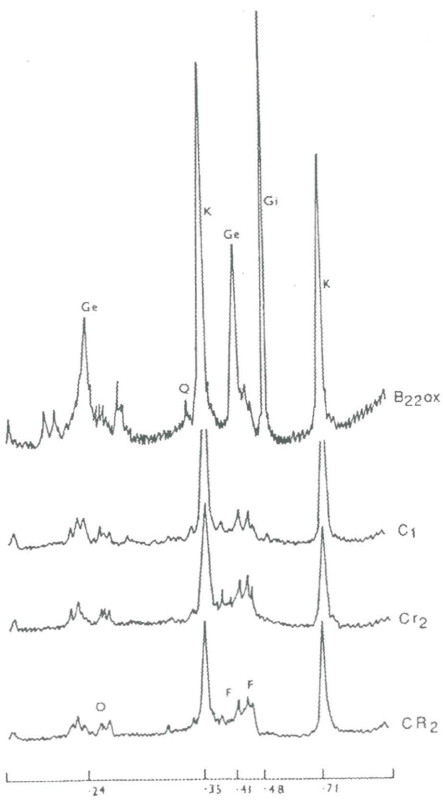

Fig. 3: The x-ray diffraction pattern of the Mg saturated clay size fraction of a basalt profile (Note: M-mica, Gi-gibbsite, Q-quartz, K-kaolinite, Ge-goethite)

The diffraction pattern of the profiles shows that the main bulk of the soil mineralogy is not detected. It is suspected that a reasonable amount of x-ray amorphous materials are present in the profile but is not detected by the diffractogram technique. The assumption is supported by the relatively high values of soil pH in 1N NaF solution, particularly in the saprolite.

From the study, the transformation of minerals from rock-saprolite-soil for basalt profile, can be proposed as follows:

<u>Rock</u>		<u>Saprolite</u>		<u>Soil</u>
Olivine	→	Goethite	→	Goethite
		Chlorite		Goethite
Augite	→	Goethite	→	Goethite
Plagioclase	→	Plagioclase	→	Kaolinite
	→	Kaolinite	→	kaolinite
	→	Gibbsite	→	Gibbsite
Opaque	→	Opaque	→	Opaque
			→	Goethite

Microfabric Observation

The study of the profile shows drastic changes in the microfabric of the rock-saprock-saprolite-soil sequence. The fine-grained basalt rock is composed of microphenocrysts of plagioclase, olivine and pyroxene. The groundmass is composed of the same three minerals together with roughly rectangular magnetite minerals. At the saprock zone, the olivine and pyroxene minerals are moderate to well altered. The matrix has an undifferentiated b-fabric and an open porphyric c/f related distribution pattern (RDP), suggesting that a certain amount of clay formation is already occurring at this layer. The massive saprock gradually developed into vughy microstructure, with the void size < 1 mm, and increased in porosity from 8% to 15%. Most primary minerals in these saprolite zones are well weathered into dark brown clayey matrix. Pseudomorphs of olivine and pyroxene are rare. The total porosity increases to approximately 50% in the soil layers, comprising dominantly packing voids. Abundant of opaque minerals and some quartz are observed. Only very few subhedral olivine and pyroxene are seen coated by iron oxides that may have protected them from weathering. The b-fabric and RDP remain the same throughout the profile.

Elemental Mobility

A study of elemental mobility during saprolite formation was conducted using isovolumetric method. The results are presented in *Fig. 4* and Table 4.

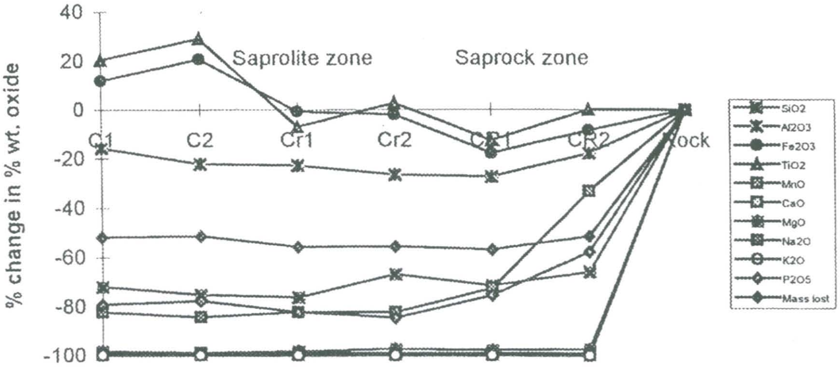

Fig. 4: The loss and gain of elements during the formation of saprolite

TABLE 4
The isovolumetric loss and gains of major and trace elements during rock transformation into saprolite

Element	Elemental content (cg cm^{-1}) Rock	Elemental content (cg cm^{-1}) Saprolite	Loss (-) and Gains (+) of elements (% total elemental content in rock) Rock – Saprolite
Major element			
SiO_2	19.0	34.0	-72
Al_2O_3	39.0	33.0	-16
Fe_2O_3	29.0	33.0	12
TiO_2	4.3	5.2	21
MnO	0.5	0.1	-82
CaO	21.0	0.2	-98
MgO	15.2	0.3	-98
Na_2O	6.2	0.1	-99
K_2O	3.3	0.0	-100
P_2O_5	1.3	0.3	-79
Trace element			
Ba	925	51	-95
Cr	1920	448	-77
Cu	77	182	136
Nb	36	75	108
Ni	241	212	-11
Sr	1356	24	-98
V	438	338	-23
Y	84	8	-90
Zn	342	149	-57
Zr	361	309	-14
Bulk Density (cg/cm^3)	241	117	

i. Mobility of Major Elements

The transformation of rock to saprolite has resulted in a total mass loss of 57.8%. During basalt weathering, most of the rock constituents are depleted significantly even at the initial stage of weathering, i.e. saprock formation. Silica depletes abruptly from 66% to 76% during the saprock and saprolite formation, respectively, and this accounts for 62% of the total mass loss. Aluminium demonstrates a gradual loss of 18 to 26%. Manganese and phosphorus decrease drastically in the saprock and are almost totally depleted in the saprolite. There is absolute impoverishment of potassium, calcium, magnesium and sodium during saprolite formation. Ferum and titanium show a slight decrease during saprock formation, but a marked enrichment in the saprolite formation. The marked depletion of these cations from the saprolite, as reported by Ferrari and Megaldi (1983), may have resulted in low soil abrasion pH (Table 5). The magnitude of the major element depletion in this profile, with decreasing order, is: K, Na, Ca , Mg > Mn , P > Si > Al > Fe, Ti.

ii. Mobility of Trace Elements

Among the trace elements studied, strontium, barium and yttrium are most mobile, in which > 90% are depleted from the saprolite. The sequence of trace element mobility, with decreasing order, is: Sr > Ba > Y > Cr > Zn > V > Zr > Ni > Cu, Nb. Copper and nobium indicate enrichment in the saprolite.

From the study, the mobility of the various elements in basaltic profile can be summarized as follows:

Most mobile : K_2O, Na_2O, CaO, MgO, Sr, Ba, and Y
Intermediate : MnO, P_2O_5, SiO, Cr, and Zn
Least Mobile : Al_2O_3, V, Zr, and Ni
Enrichment : TiO_2, Fe_2O_3, Cu, and Nb

Weathering Pattern

Various weathering indices were analyzed and assessed for their applicability to determine the degree of weathering in basalt profile (Table 5). All indices show a very drastic change in the distribution pattern with depth at the saprock zone, obviously suggesting that an intense stage of weathering has occurred even at the early weathering of basalt. At this point, it is possible to say that basalt rock may have actually transformed directly into saprolite. The high weatherability of basalt in humid tropical climate, as in the study area, may have resulted in such phenomena. The weathering pattern in the saprolite and soil layers show a gradual change, yet already at the extreme stage.

CONCLUSIONS

The study suggests that weathering in this profile is intense and rapid, even at the lower saprolite layers. This is indicated by the changes in the physico-chemical properties, charge characterization, and drastic transformation of weatherable minerals into secondary forms. The regolith is characterized by drastic change in bulk density and soil abrasion pH values, high free iron content and P sorption index, as well as low aluminium content. The low CEC and base saturation, even at the deepest horizons, suggest that extensive leaching has taken place (Burnham 1989; Hamdan 1995), attributed to

TABLE 5
The degree of weathering as determined by various weathering indices

Horizon	Molar Ratio SiO_2/Al_2O_3	Silt/Clay Ratio	WIP	Abrasion pH	RAI
Ap	1.14	0.16	0.17	4.20	3.50
B2ox	1.11	0.16	0.90	4.50	3.40
BC	1.29	0.21	1.30	4.80	3.20
Upper saprolite	1.66	0.32	1.40	4.80	2.10
Middle saprolite	1.81	0.35	1.50	4.80	1.60
Lower saprolite	2.18	1.86	2.00	4.95	1.53
Rock	5.22	nd	104.4	8.90	0.44

Note: WIP - Weathering Index of Parker
RAI - Rock Alteration Index

the significant depletion of bases during saprolitization. This may explain why soils in the humid tropics are relatively low in fertility (Hamdan and Burnham 1996). In this case, the contribution of nutrients from basalt weathering seems insignificant. The atmospheric inputs and the recycling of organic inputs are therefore important to sustain minimum level of soil fertility in the tropics. The mineralogy of the parent rock as well as climatic influence, perhaps attribute markedly to accelerate weathering processes in this soil type, that consequently does not reflect its age of deposition (Hutchison 1973).

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