

The Mineralogy and Chemical Properties of Soils on Granite Gneiss in Three Climatic Zones in Sri Lanka

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ABSTRAK

Granit gneis dijumpai wujud di merata-rata di Sri Lanka. Bergantung kepada keadaan iklim dan topografi kawasan, bahan ini mengalami luluhawa kimia yang berbeza-beza. Satu kajian mineralogi dan sifat kimia keatas sifat tanah granit gneis daripada tiga zon agro-ekologi di Sri Lanka telah dijalankan. Tanah dalam zon lembab didapati rendah pH dan kation bertukar ganti, manakala tanah dalam zon kering pula mempunyai pH dan kation bertukar ganti yang tinggi. Warna tanah bertukar daripada coklat kekuningan kepada merah apabila tanah bertambah kering mungkin disebabkan oleh kehadiran hematit dan/atau goethit. Kaolinit, haloisit dan smektit wujud di dalam semua tanah tanpa mengira iklim; amaun haloisit berkurangan menghala ke permukaan tanah. Boitit wujud dengan banyaknya di dalam tanah zon perantaraan dan kering, tetapi tidak wujud dalam tanah zon lembab. kepekatan Ca dalam larutan tanah bergantung kepada amaun Ca yang wujud dalam bentuk bertukar ganti. Tambahan lagi, kepekatan Ca larutan berkolerasi secara bererti dengan EKPK dan nisbah EKPK/KPK tanah.

ABSTRACT

Granite gneiss occurs sporadically throughout Sri Lanka. Depending on the climatic conditions and topography of the area, the rock undergoes different degrees of chemical weathering. The mineralogy and chemical properties of four common granite gneiss soils occurring in three agro-ecological zones in Sri Lanka were studied. The soil in the wet zone is low in pH and basic exchangeable cations, while the soils in the wet zone are high in pH and basic exchangeable cations. The colour of the soils changes from yellowish-brown to red as the soils get drier, presumably due to the presence of haematite and/or goethite. Kaolinite, halloysite and smectite are present in all the soils irrespective of the climatic conditions; the amount of halloysite decreases towards the surface. Biotite is abundant in the soil of the intermediate and dry zones, but is absent in the soil of the wet zone. Gibbsite is present in the highly weathered soil of the wet zone. The concentration of Ca in soil solution is dependent on the amount in the soils existing in the form of exchangeable Ca. Additionally, the solution Ca concentration is significantly correlated with the soil ECEC and the ECEC/CEC ratio.

INTRODUCTION

Sri Lanka, located near the Equator, is agro-ecologically divided into wet, intermediate and dry zones (Anon 1979). The wet zone occurs in the southwest, while the dry zone occurs in the north (Fig. 1). The middle part of the country

receives intermediate rainfall. Soil physico-chemical properties and agricultural production in the country are closely related to the rainfall patterns in the different agro-ecological zones.

The southern part of Sri Lanka is dominated by red yellow podzolic and latosolic soils (Anon

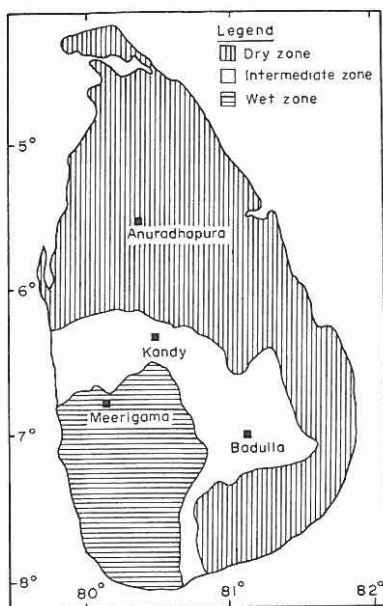


Fig. 1: A map of Sri Lanka showing agro-ecological zones (Anon. 1979) and the sites of soil sampling

1979). Besides red yellow podzolic soils, reddish brown earth occurs in the intermediate zone. These soils can either be classified as Ultisols or Alfisols in soil taxonomy (Soil Survey Staff 1992). The soils in the middle and northern parts of the country are different from those of the south due to differences in the rate of leaching and chemical weathering; the rainfall in the north is much lower than in the south. The colour of these soils is determined primarily by the type of Fe mineral rather than the absolute amount of Fe oxide present in the soils. According to Schwertmann (1993), haematite-

containing soils have mostly hues between 5YR and 10R, whereas goethite-containing soils with no haematite have hues between 7.5YR and 2.5Y.

Granite gneiss is an important rock type in Sri Lanka, and many soils earmarked for agricultural and/or forestry purposes are derived from it. The granite gneiss occurs sporadically throughout the three agro-ecological zones of Sri Lanka. Biotite (iron magnesium mica) is one of the major minerals in the granite gneiss (Paramanathan 1977). According to Eswaran and Heng (1976), biotite transformed to halloysite, kaolinite or goethite depends on the position of the mineral in a weathering profile. Due to differences in the climate and topography, the granite gneiss soils in Sri Lanka that have undergone different degrees of weathering are differentiated into Ultisols and Alfisols. Mineralogical transformation and soil solution chemical composition in the different agro-ecological zones have not been investigated and documented in Sri Lanka. The objective of this paper is to characterize the mineralogy and soil solution chemical composition of some of the common granite gneiss soils in the three agro-ecological zones in Sri Lanka.

MATERIALS AND METHODS

Soils

The soil profiles for this study were examined during a field tour in Sri Lanka in October 1991 (Shamshuddin and Ahmad Husni 1992). The soils, derived from granite gneiss, were sampled at four localities, representing the three agro-ecological zones in Sri Lanka (Fig. 1). The soils

TABLE 1
Location, annual rainfall, agro-ecological zone and colour classification of the soils under investigation

Location	Rainfall mm/year	Agro-ecological zone	Subsoil colour	Subgroup
Meerigama	4008	Wet	Yellowish brown	Typic Hapludults
Badulla	1800	Intermediate	Red	Typic Hapludults
Kandy	1563	Intermediate	Red	Typic Rhodustalfs
Anuradhapura	1329	Dry	Red	Typic Rhodustalfs

TABLE 2
Relevant chemical properties of the soils under investigation

Location	Depth (cm)	Horizon	pH(1:1)		Exchangeable Cations					ECEC	CEC	Fe ₂ O ₃	Teture (mm)		
			H ₂ O	CaCl ₂	Ca	Mg	K	Na	Al				cmol _c /kg	<2 %	2-50
Meerigama	0-9	Ap	5.4	4.8	1.52	0.55	0.04	0.13	0.20	2.44	3.99	0.4	4.8	8.3	86.6
	9-34	Bw	5.2	4.1	0.49	0.40	0.04	0.03	0.20	1.16	3.26	0.4	9.8	8.6	81.2
	34-65	Bt ₁	5.2	3.9	0.53	0.55	0.04	0.05	0.10	1.27	4.43	0.6	14.3	4.8	80.8
	65-85	Bt ₂	5.3	3.8	0.08	0.75	0.04	0.08	4.00	5.67	8.98	1.2	31.1	6.2	62.1
	85-120	Bt ₃	5.1	3.8	1.12	0.54	0.04	0.09	5.10	6.89	11.92	1.2	30.1	12.8	56.8
Badulla	0-26	Ap	5.5	5.0	3.00	1.43	0.45	0.08	0.10	5.78	16.48	9.4	14.0	56.7	28.8
	26-63	Bw	5.3	5.1	3.01	4.09	0.38	0.52	0.30	8.30	10.50	8.5	60.5	14.1	25.1
	63-98/104	Bt ₁	5.9	5.6	3.03	6.72	0.09	0.19	0.10	13.13	17.21	10.4	64.1	17.4	18.2
	98/104-135	C ₁	5.2	4.9	4.25	51.21	0.18	0.32	0.010	56.06	34.83	3.4	34.7	18.0	46.5
	135+	C ₂	6.4	5.7	4.00	52.60	0.27	0.54	0.10	57.51	13.24	2.5	14.5	12.9	72.2
Kandy	0-14	Ap	6.4	6.2	12.00	0.58	0.29	0.57	0.10	13.54	14.71	3.0	27.8	5.6	66.5
	14-49	Bt ₁	6.0	5.5	10.10	2.43	0.31	0.27	0.10	13.22	14.12	3.4	34.7	6.2	58.8
	49-97	Bt ₂	6.3	5.7	11.70	3.38	0.16	1.31	0.10	15.65	16.77	4.0	44.8	5.8	49.1
	97-130	Bt ₃	6.3	5.7	10.85	5.52	0.27	0.48	0.20	17.22	17.50	4.3	46.0	5.7	48.0
	130+	Bt ₄	7.0	6.1	9.40	5.45	0.13	0.22	0.10	15.40	16.63	4.0	40.4	7.9	51.7
Anuradhapura	0-9	A ₁	6.4	6.1	10.69	1.61	0.54	0.95	0.10	13.89	9.57	1.8	16.2	5.8	77.7
	9-24	Bt ₁	6.1	5.6	6.28	1.65	0.32	0.48	0.10	8.83	9.72	2.5	24.3	9.1	66.2
	24-65	Bt ₂	6.3	5.4	7.23	2.07	0.18	0.32	0.10	9.90	10.74	2.9	32.3	8.4	58.9
	65-120	Bt ₃	6.2	5.3	7.69	2.11	0.13	0.24	0.10	10.27	12.51	3.1	35.9	9.3	54.3
	120-140/150	Bt ₄	6.3	5.2	8.25	0.32	0.22	0.20	0.20	9.15	12.65	2.7	34.9	8.1	56.7

are classified either as Hapludults, Haplustalfs or Rhodustalfs (Table 1), based on their chemical properties (Table 2) or on profile morphology (data not shown).

Methods

pH in water and 0.01 M CaCl₂ was determined after 1 h of intermittent shaking and an overnight stand. CEC was determined by 1 M NH₄OAc buffered at pH7. Basic exchangeable cations were extracted by 1 M NH₄OAc; Ca and Mg were determined by atomic absorption spectrophotometry, while K and Na were determined by flame photometry. Exchangeable Al was extracted by 1 M KCl and determined colorimetrically (Barnhisel and Bertsch 1982). ECEC was calculated as the sum of basic exchangeable cations and exchangeable Al. Free iron oxide was determined by the method of Mehra and Jackson (1960). Texture of the soils was determined by the pipette method of Day (1965). The mineralogy of the clay fraction from the topsoil and the subsoil was determined by XRD analysis and TEM. The XRD analysis was conducted using a Philips diffractometer equipped with a graphite monochromator, operated from 3 to 50 degrees 2 - theta at a scanning speed of 1/2 degree per minute. Selected samples were subjected to further tests in order to confirm the presence of smectite and chlorite.

Distilled water was added to the air-dried soils and subsequently incubated for 1 day at a matric suction of 10 kPa (Menzies and Bell 1988). This study assumes that a state of equilibrium is reached between the liquid and solid phase of the soils during the incubation period. Soil solutions were extracted by centrifugation at 2000 rpm for 1 h. pH and EC were determined immediately from 2-ml subsamples. The rest of the solutions were stored at 5°C for determination of Ca, Mg, Na, K, Al, Mn, Fe, P and S by inductively coupled plasma atomic emission spectroscopy (ICPAES). Nitrate in the soil solutions was determined by an autoanalyser.

RESULTS AND DISCUSSION

Soil General Properties

Rainfall distribution pattern in the areas covered by granite gneiss in Sri Lanka is variable, having values ranging from 4008 mm p.a. in Meerigama to 1329 mm p.a. in Anuradhapura

(Table 1). The effects of rainfall on the soils are manifested clearly by soil pH and the amounts of basic exchangeable cations present. Where rainfall is high (Meerigama), basic exchangeable cations are low and the basic cations are lost via leaching. pH (CaCl₂) is < 5, thus the soil is acidic in reaction (Table 2). The topsoil from the intermediate agro-ecological zone (Badulla) contains reasonable amounts of basic exchangeable cations. Here the soil pH is higher than that at Meerigama. The basic exchangeable cations and the soil pH increase further as the rainfall decreases. This is shown clearly by the high pH value in the soil at Anuradhapura, where topsoil pH (CaCl₂) is higher than 6.

The exchangeable basic cations in the soils subjected to high rainfall (Meerigama) are low (Table 2) and exchangeable Al in the topsoil is also low, but at depths below 65 cm, the exchangeable Al is > 4 cmol_c/kg soil. However, in drier areas (Kandy and Anuradhapura), the basic exchangeable cations are very high, especially the exchangeable Ca. As pH in these soils is high, exchangeable Al is only present in trace amounts. Aluminium in the soil solution precipitates as Al(OH)₃ as pH approaches 5.5.

Exchangeable Mg in the C horizons of the soil at Badulla is extremely high, having values exceeding 50 cmol_c/kg soil (Table 2) which is presumably related to the presence of weathered ferromagnesium minerals in the granite gneiss. The typical Mg-bearing minerals in granite gneiss are biotite, pyroxene and amphibole, which on weathering become smectite if conditions are favourable for its formation. The high CEC (in terms of cmol_c/kg clay) observed in the C horizons points to the presence of this mineral.

The colour of the soils in the B horizon changes from yellowish brown (10YR 5/6) to red (2.5YR 4/6) and is presumably attributed partly to the presence of goethite and/or haematite which, in turn, depends on the availability of moisture in the soil profiles. The red soils occurring in the intermediate and dry zones, which are classified as Rhodustalfs, are normally associated with the presence of these Fe minerals. Haematite is coloured 5R to 2.5 YR (Bigham *et al.* 1978), while goethite is 7.5 YR to 10 YR (Kitagawa 1983). Goethite tends to impart yellowish brown to brown colours to soils (Allen and Hajek 1989). The soils studied are very deep, except the soil at Badulla site, which is seriously eroded. The Badulla site is located at

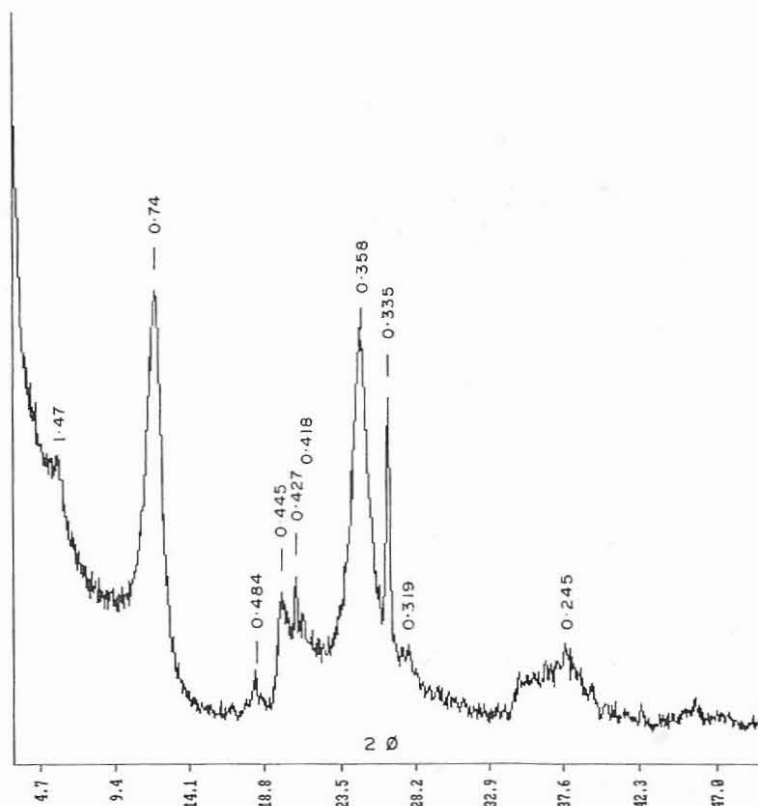


Fig. 2: X-ray diffraction pattern of Mg-saturated clay fraction from the Ap horizon of the soil at Meerigama

659 m k.a.s.l., on rugged topography having a slope of 100%. The topsoil is constantly removed by geological erosion during rainy months. Morphologically, the soil is not highly weathered as rock fragments containing weatherable minerals were observed in the B horizon.

Overall, the four soils under study are sandy in nature, an inherent physical property of the soils derived from granite gneiss, which is essentially composed of quartz, feldspar and biotite (black mica), with minor amounts of ferromagnesium minerals. The CEC (on the basis of 1 kg clay) is high, suggesting that some of the soils contain some smectite or mica-smectite mixed-layers. These minerals are the alteration products of biotite weathering under impeded drainage conditions (Velde 1992).

Mineralogy

The XRD analysis of the clay fraction from the Ap horizon of the soil at Meerigama shows the

presence of smectite (1.47 nm), halloysite (0.74, 0.445 nm) kaolinite (0.358 nm) and quartz (0.427, 0.335 nm), with minor amounts of gibbsite (0.484 nm), feldspar (0.319 nm) and goethite (0.418, 0.245 nm) (Fig. 2). The subsoil showed similar mineralogy. Though present in minor amounts, goethite imparts yellowish brown 10 YR 5/6 colours to the soil (Kitagawa 1983; Allen and Hajek 1989). There are no biotite reflections in the diffractogram. The biotite present in the original rock could have been transformed completely to halloysite (Paramanathan 1977) and/or goethite under the strongly leaching environment (Eswaran and Heng 1976). In the humid tropics, biotite can also be transformed to kaolinite (Eswaran and Heng 1976). The halloysite and quartz XRD peaks are sharp and intense, showing their dominance in the clay fraction. The presence of smectite is also reflected in the high CEC (calculated on the basis of 1 kg clay), but the smectite is not clearly manifested in the TEM micrographs as smectite crystals are very small (Plate 1A, B).

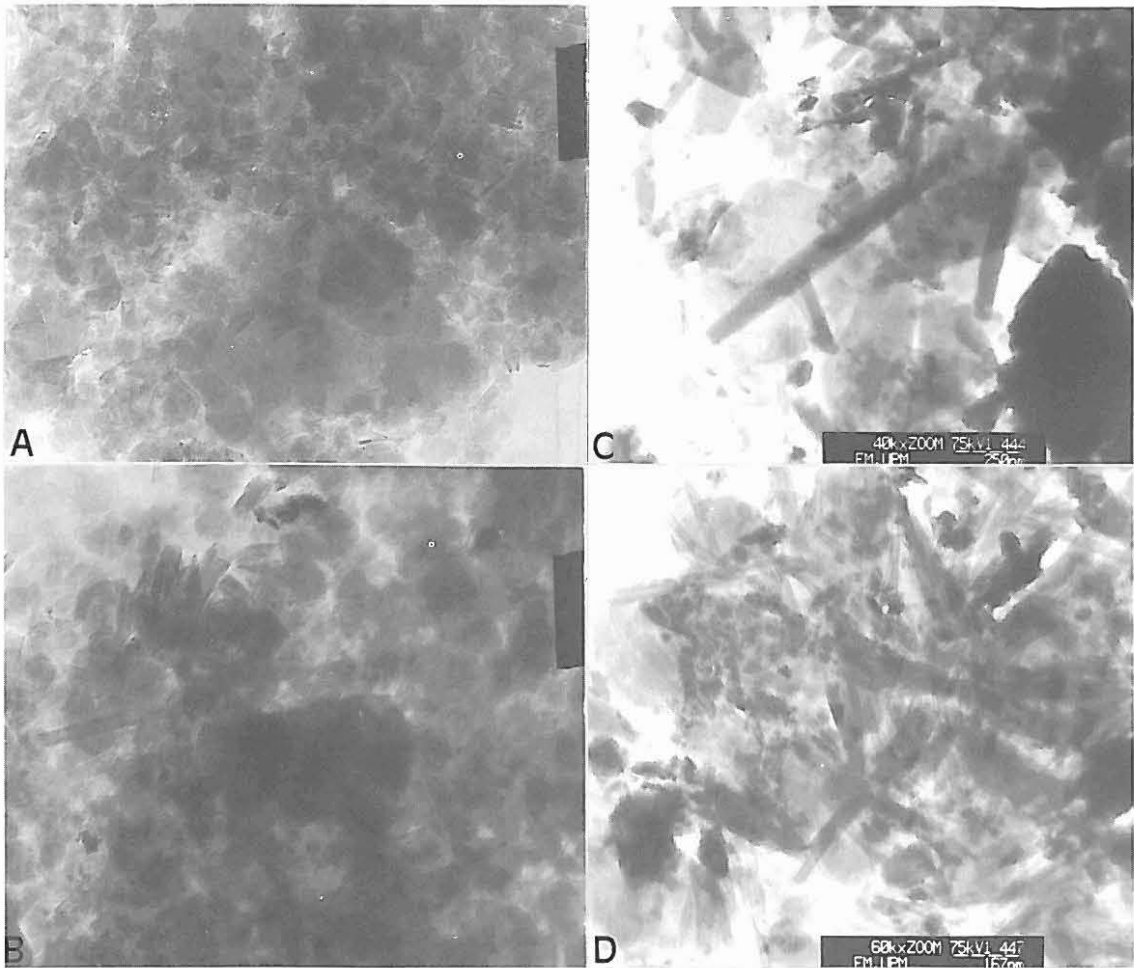


Plate 1. TEM micrograph of the clay fraction from the Ap (A) and Bt₃ (B) horizon of the soils at Meerigama and from the A₁ (C) and C₁ (D) horizons of the soils at Badulla

The TEM micrographs show clearly the presence of a mixture of halloysite and kaolinite in the clay fraction of the soil; the halloysite crystal is tubular while the kaolinite crystal is hexagonal in shape. The amount of halloysite decreases towards the soil surface, while kaolinite increases, which is similar to the observation of Paramananthan (1977) in the granite gneiss soil of Malaysia. This is an indication that halloysite changes to kaolinite in the course of soil weathering. X-ray diffraction pattern of the clay fraction from the Bt₃ horizon is similar to that of the Ap, showing a similar type of mineralogy in the soil of both horizons.

The topsoil at the Badulla site has sharp XRD reflections at 0.72 and 0.356 nm, suggesting the presence of large amounts of kaolinite (Fig. 3). Biotite is absent in this horizon al-

though the XRD pattern of the clay fraction from the C₁ horizon indicates the presence of some biotite, shown by a weak reflection at 1.0 nm (data not shown). The biotite in the topsoil could have been transformed completely to goethite, halloysite or kaolinite as shown in the earlier studies (Eswaran and Heng 1976; Paramananthan 1977). The presence of goethite is shown by the reflections at 0.416, 0.269 and 0.242 nm (Fig. 3). Some smectite is present in the topsoil as is shown by a weak 1.43 nm reflection. However, the amount of smectite in the C₁ horizon is very high; the XRD reflection at 1.43 nm is very strong and intense (data not shown). Halloysite is present in small amounts in the topsoil; the amount increases in the subsoil (Plate 1C, D). This phenomenon is similar to the earlier observa-

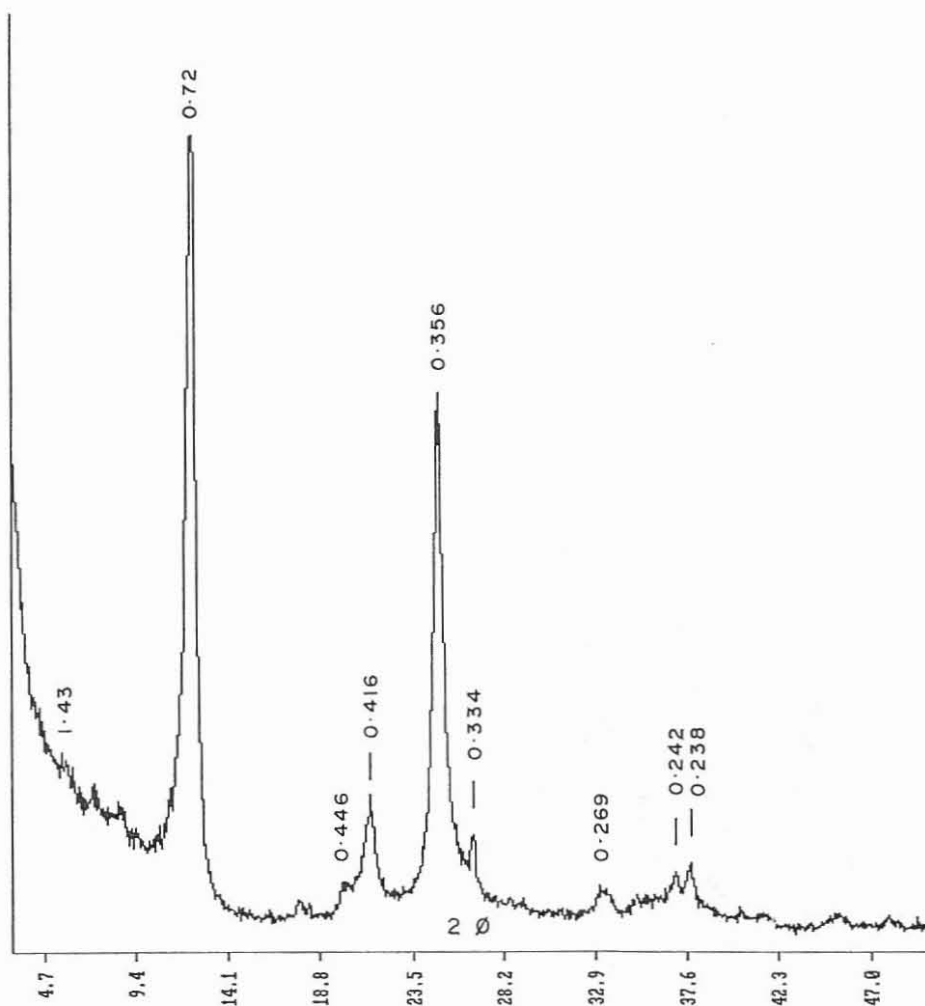


Fig. 3: X-ray diffraction pattern of Mg-saturated clay fraction from the Ap horizon of the soil at Badulla

tion in the TEM micrographs of the soil at the Meerigama site.

Smectite (1.53 nm), biotite (1.01, 0.499, 0.334 nm), quartz (0.425, 0.334 nm) and kaolinite (0.72, 0.355 nm) are the dominant minerals in the topsoil at the Kandy site (Fig. 4). Halloysite (0.445 nm) is present in minor amounts. The dominance of kaolinite is further confirmed by TEM observation (Plate 2A). The clay minerals in the subsoil are coated with Fe oxides (Plate 2B) as the amount of Fe_2O_3 in the soil is moderately high (Table 2). They are mostly present in the form of haematite (0.270, 0.251 nm) and goethite (0.270, 0.245 nm). The dominance of smectite in the soil is reflected by the high CEC; the CEC values throughout the

profile are $> 37 \text{ cmol}_c/\text{kg}$ clay. The amount of halloysite in the subsoil is higher than in the topsoil, as is shown by the appearance of 0.74 nm reflection in the XRD diffractogram from the Bt_4 horizon (data not shown). Some of this halloysite, which is tubular in morphology, can be seen in the TEM micrograph in Plate 2B.

The A_1 horizon of the soil at Anuradhapura is dominated by biotite (1.02, 0.335 nm), quartz (0.426, 0.335 nm), halloysite (0.73, 0.446 nm), smectite (1.57 nm) and kaolinite (0.357 nm), with some feldspar (0.324 nm) and haematite (0.270, 0.251 nm) (Fig. 5). Plates 2C and D show the presence of some of these minerals in the clay fraction of the soil. The morphology of the halloysite and kaolinite is not clearly mani-

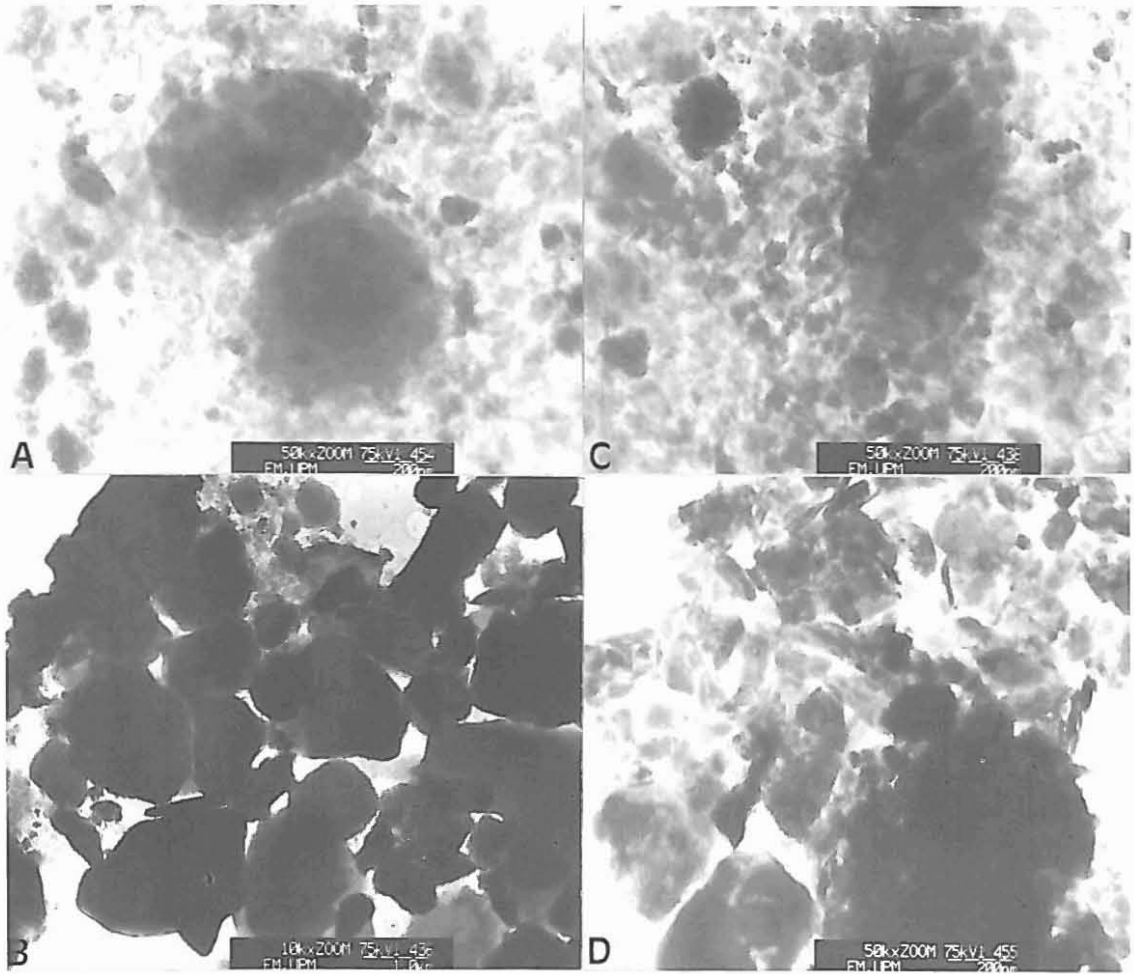


Plate 2: TEM micrographs of the clay fraction from the Ap (A) and Bt₄ (B) horizons of the soils at Kandy and from the A₁ (C) and Bt₄ (D) horizons of the soils at Anuradhapura

festes because the minerals are coated with Fe oxides, similar in nature to that of the soil at Kandy. The iron minerals are haematite, as is shown by the very clear XRD reflections at 0.270 and 0.251 nm. For this reason, the soil at Anuradhapura is red (2.5YR 4/6), and hence classified as Rhodustalf (Table 1). There is no evidence of the presence of goethite in the topsoil. The soil colour would have been yellowish brown to yellow if goethite is the dominant form of Fe mineral in the soil (Schwertmann 1993). In the Bt₄ horizon, however, some goethite was present together with haematite (data not shown). Other minerals in the clay fraction are similar to those found in the A₁ horizon.

The 0.270 and 0.251 nm reflections are more intense in the diffractogram of soil at Anuradhapura compared with that at Kandy,

indicating that the amount of haematite is higher in the soil at Anuradhapura. According to Bigham *et al.* (1978) haematite is transformed to goethite as soil moisture increases. Therefore, the soils in the intermediate and wet zones do not have haematite and the form of Fe minerals is goethite. The presence of goethite in the Bt₄ horizon of the soil at Anuradhapura is a clear manifestation of the availability of some moisture in that horizon.

Gibbsite is absent in the soils at Kandy and Anuradhapura, but present in the soil of the wet zone. This suggests that gibbsite, which is an alteration product of feldspar, can only be formed if the moisture and temperature are sufficiently high. Gibbsite is a common mineral in the soil at an advanced stage of weathering.

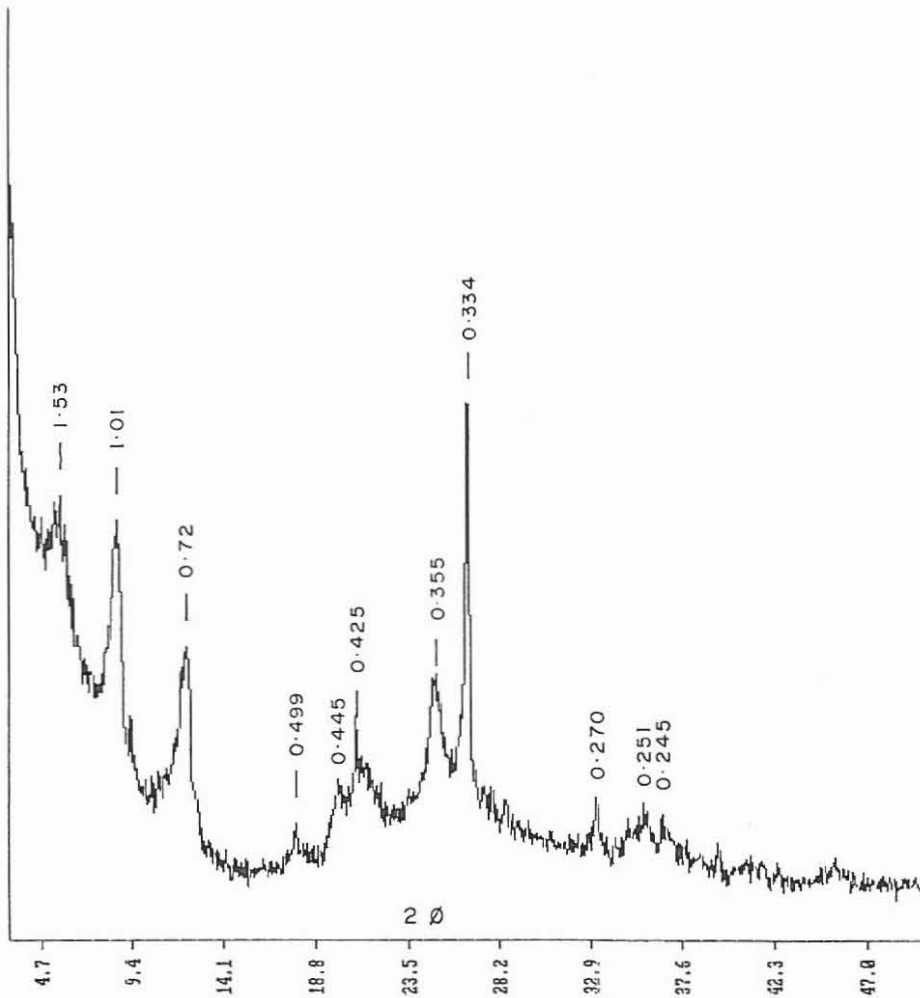


Fig. 4: X-ray diffraction pattern of Mg-saturated clay fraction from the Ap horizon of the soil at Kandy.

The Chemical Properties of Soil Solution

Generally, the soil solution Al concentration is low. High values are only observed in the Bt₄ horizon of the soils at Kandy and Anuradhapura, having values of 177 and 76 μM, respectively (Table 3). More Al is present in the soil solution of the drier area. Al is expected to exist as Al(OH)₃ which is the normal Al species stable at high pH. Mineralogical investigation reveals that the soils are dominated by kaolinite, halloysite and oxides of Fe, which are termed variable-charge minerals. This means that the negative charge on the soil surfaces increases with increasing pH (Uehara and Gillman 1981). Negative charge is, therefore, high at high pH, when Al is held tightly by the soil surfaces.

Consequently, the soil solution Al concentration is low.

The soil solution pH (Table 3) is comparatively higher than the soil pH (Table 2). Lower pH_{CaCl2} value compared to pH_{sol} is due to greater hydrolysis of Al in solution of the former; CaCl₂ solution can extract more Al than water. The soil solution pH is related to the pH_{CaCl2} by the following equation:

$$pH_{sol} = 4.56 + 0.52 pH_{CaCl2} \quad (r = 0.68, \quad p < 0.05)$$

Although the basic exchangeable cations in the soils are high, their concentrations in the soil solution are low, except in soil solution Na concentration. It is believed that the cations are

TABLE 3
pH, EC and elemental composition of the soil solutions

Location	Horizon	pH	Elemental composition of the soil solutions										
			EC (mS/cm)	Ca	Mg	K	Na	Al mM	Fe	Mn	P	S	No ₃
Meerigama	Ap	6.9	63	250	185	249	470	23	21	8	10	396	3507
	Bt ₁	6.9	53	37	27	27	669	2	1	4	35	92	tr
	Bt ₃	6.2	59	18	6	18	1078	10	2	tr	3	27	tr
Badulla	Ap	7.0	44	152	199	234	154	3	tr	69	13	328	1856
	Bt ₁	7.2	20	84	122	27	160	11	tr	1	16	43	766
	C ₁	7.6	74	207	643	63	166	7	tr	10	81	125	1202
Kandy	Ap	8.4	207	2478	1393	324	444	2	2	26	52	933	1856
	Bt ₁	8.2	179	964	385	55	325	2	1	14	13	111	549
	Bt ₄	7.3	50	170	158	55	160	177	22	1	21	70	608
Anuradhapura	A ₁	7.5	175	1946	860	976	511	9	tr	tr	41	520	1202
	Bt ₁	7.0	71	170	78	39	224	47	6	3	39	88	tr
	Bt ₄	6.9	35	132	76	37	624	76	10	tr	26	135	tr

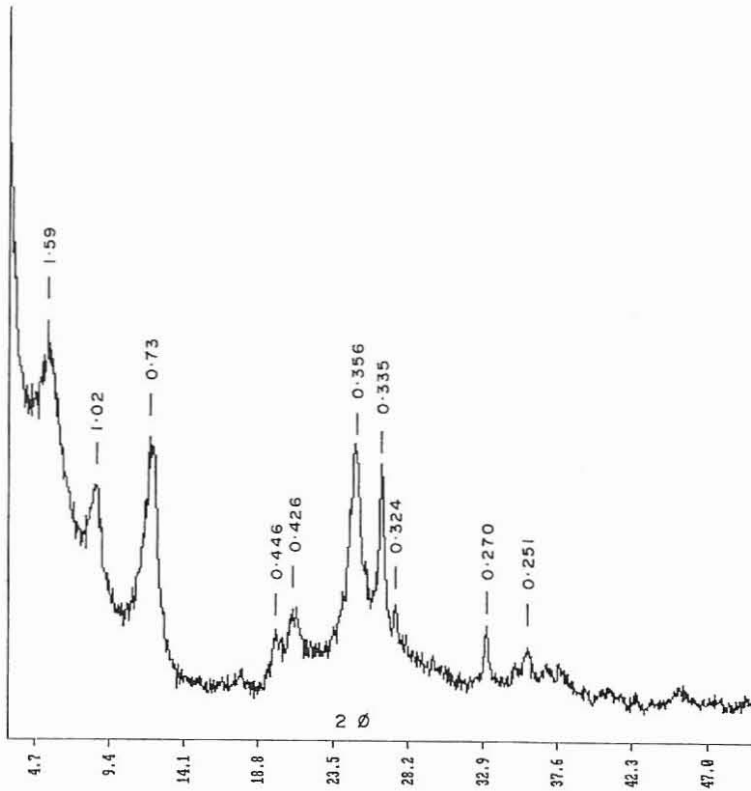


Fig. 4: X-ray diffraction pattern of Mg-saturated clay fraction from the A₁ horizon of the soil at Anuradhapura

strongly held to the soil surfaces because of the high CEC, contributed by smectite and/or being produced by the variable-charge minerals as a result of high pH. Nevertheless, the soil solution Ca concentration is highly correlated with the exchangeable Ca, and the relationship is represented by this equation:

$$Ca_{sol} = 311 + 147 Ca_{exch} \quad (r = 0.74, P < 0.01)$$

The exchangeable Ca in the Ap and A₁ horizons of the soils at Kandy and Anuradhapura are 12.00 and 10.69 cmol_c/kg, respectively (Table 2). The corresponding soil solution Ca concentrations are 2478 and 1946 μM (Table 3). The soil solution Ca concentration is higher in the dry than in the wet zone (Table 3). The Ca concentrations of soil solutions at the Meerigama, Kandy and Anuradhapura sites increase with depth. The soil solution Ca concentration is also highly correlated with the ECEC (calculated on the basis of 1 kg clay). The relationship is given by the following equation:

$$Ca_{sol} = 1.28 ECEC^{1.47} \quad (r = 0.91, P < 0.01)$$

In addition, the soil solution Ca concentration is related to the ECEC/CEC ratio by the equation:

$$Ca_{sol} = 342 ECEC/CEC^{1.74} \quad (r = 0.59, P < 0.05)$$

In contrast, the soil solution Mg and Al concentrations are not significantly correlated with any of the above-mentioned parameters.

CONCLUSION

The mineralogy and chemical properties of the soils in the three agro-ecological zones in Sri Lanka are different. Where the annual rainfall is high, soil pH and basic exchangeable cations are low. In the drier areas where leaching is restricted the pH and basic exchangeable cations are high. Kaolinite, halloysite and smectite are the major minerals in all the soils irrespective of the climatic conditions. While the amount of haematite increases as the soil get drier, the amount of goethite decreases, and consequently

the colour of the soils becomes redder. In the wet zone, some gibbsite is present. The availability of Ca in the soil is dependent on the exchangeable Ca, ECEC and the ECEC/CEC ratio. These soil solution attributes can be used as indices of Ca availability for crop growth in the soils developed over granite gneiss in Sri Lanka.

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