Incipient Weathering of Granite-Gneiss and Soil Development in Southwestern Nigeria

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Abstract

The effects of intensive leaching of granite-gneiss by the tropical rainfall, acidified carbonated water and simple aliphatic (citric) and aromatic (salycyclic) organic acids at the onset of rock weathering were investigated by simulated weathering for 10 weeks. The results indicated that at the initial stage of weathering of granite-gneiss under humid tropical condition with particular reference to southwestern Nigeria, more Mg and Ca were leached from the medium grained granite-gneiss than the coarse textured equivalent. In terms of relative ease with which the different elements were leached, Na~Mg~K>Ca>SiO_2, while Fe and Al concentrations in the leachates were below the detection limit (0.001 mg/kg). The presence of mostly acidic parent rock with low content of basic cations in an area of acidic rain (rain water *p*H 5.14 - 6.45), high rainfall (>1300 mm/yr) with greater than 0.8 PET and high soil temperature (27-31 °C at 50 cm soil depth) are factors considered to enhance hydrolytic weathering in the region. The hydrolytic weathering plus the climatic, geologic and physical setting of the region appear to predispose the rocks to ferrallitic pedogenesis.

Introduction

Weathering precedes soil formation and it is a continuing process during soil development. Weathering relates to the chemical and physical disintegration and decomposition of rock and minerals contained in them (Buol *et al.*, 1980). Progressive fragmentation of the initial rock and plasmification of the component weatherable minerals (Eswaran, 1997), otherwise termed arenisation (Millot, 1970), is one of the most important initial stages of weathering of granites. In the humid tropics, intensive weathering is associated mainly with pronounced leaching, and the principal factors commonly suggested to encourage rapid leaching are high and acidic precipitation, year round high soil temperature, mineralogical composition of the parent material and the contributions of organic acids.

The role of simple organic acids in mineral weathering has been demonstrated in laboratory experiments in which the acids caused accelerated mineral dissolution and selective release of some elements (Henin & Pedro, 1965; Boyle *et al.*, 1974;Manley and& Evans, 1986). It was suggested that water soluble, low molecular weight organic acids entering the soil as microbial metabolites or plant exudates from living or dead cells, together with microbial oxidation products of humic substances or lignin polymers are the likely organic compounds involved (Manley & Evans, 1986). The concentrations of such acids in soils are generally in the range of 10^{-3} to 10^{-5} *M*.

It was observed that six (Boyle *et al.*, 1974) and 16 (Manley & Evans, 1986) organic acids extracted greater percentages of Fe, Mg and Al than inorganic acids of similar strength. These workers, however, based their studies on single minerals, yet weathering and soil formation are complex processes involving simultaneous distintegration, decomposition and transformation of a variety of minerals within the rock-saprolite soil sequence (Eswaran, 1979; Buol *et al.,* 1980). Therefore, the objective of this study was to examine the effects of organic acids and acid precipitation on the initial stage of granite-gneiss weathering under humid tropical condition with a view to better understanding rock transformations at the early stage of pedogenesis. This will help to gain insight into the dominant pedogenetic processes evolving the soils.

Materials and method

Description of the study area

The study area was located within latitude 07^0 10^l and 07^{0}37^{l}N, and longitudes 004^{0}30^l and 05^0 00^{l}E. It is a region within the forest central southwestern Nigeria. The area is gently undulating (2-8% slope) with occasional steeply sloping (>30% slope) rock outcrops (inselberg). A major town, Ile-Ife (07^0 28^l and 004^0 33^{l}E) within the study area, is 800 m above mean sea level (Ojo-Atere *et al.*, 1987). The area is characterized by distinct dry (November-early March) and wet (mid March - October) seasons. Rainfall pattern is bimodal with peak periods in June and September with mean annual rainfall of about 1300 mm. Mean monthly atmospheric and soil temperature at 50 cm depth ranges from 27.1 -34.4 °C and 27.1-31.0 °C, respectively (Table 1). The climax vegetation in the area was described as tropical high forest with a dominant tree vegetation (Keay, 1949). The granite-gneiss bedrock in the area forms part of the Precambrian Basement Complex in Nigeria. Isotopic evidence indicated that its emplacement dates back to the Pan-African orogeny, about ± 150 m.a. (Ojo-Atere *et al.*, 1987).

The greater part of southwestern Nigeria is underlain by the the migmatite gneiss-quartzite complex (Rahaman, 1988), and the coarse and medium-grained granite-gneisses are important and widespread members of this petrological complex. The coarse textured granite-gneiss gives rise to a group of soils found to be repeatedly associated along toposequences in the area. The soils are locally classified as Iwo Association, named after the most important

TABLE 1

Climatic data for the study area (1975-1998)

Period of the year	*Air temp. (°C)*	*Soil temp. (°C) at 50 cm depth*	*Rainfall (mm)*	**PET (mm)*	*Climatic water balance*
January	32.2	28.7	13.0	119.0	0.11
February	34.4	30.4	21.1	125.8	0.17
March	33.6	31.0	60.5	115.9	0.52
April	32.1	30.6	125.1	74.3	1.62
May	30.9	29.8	170.0	55.4	3.07
June	29.5	28.7	202.3	38.8	4.15
July	27.1	27.5	183.4	37.2	4.93
August	27.1	26.9	157.8	37.6	4.24
September	27.9	27.1	224.0	37.5	5.97
October	29.5	28.3	167.4	44.2	3.79
November	32.1	29.0	10.4	66.2	0.16
December	32.0	29.0	7.8	106.5	0.07

** PET = Potential Evapotransipration*

series in the association; while those on medium-grained granite-gneiss are also geographically classified as Ondo Association (Smyth & Montgomery, 1962).

The simulated weathering procedure

Fresh (unweathered) samples of the rocks (coarse and medium grained granite-gneiss) were collected for the study. The mineralogical composition of the rocks was established by preparing thin sections following the procedure in Wahlstrom (1960), and by examining the thin sections under plane polarized light and also using crossed-polars. Modal analysis of the minerals was carried out using a swift automatic electric point counter at a point spacing of 0.05 mm. Elemental analysis of the rocks was carried out by solubilizing in hydrofluoric (HF)-perchloric ($HClO_4$)-sulphuric (H_2SO_4) acids mixture, and using the atomic absorption spectrophotometer (AAS) to read the concentration of the elements. Fresh samples of the rocks were ground into very fine powder (to pass through 100-mesh sieve) with a roller - crusher and high-speed hammer mill to create greater surface area.

The simulated weathering involved leaching the powdered rock samples (20 g per leaching chamber) with different leaching solutions. The leaching columns consisted essentially of three parts: the irrigation system, a drainage system and a sample chamber as described by Sehgal *et al.* (1972). Leaching solutions were basically five, *viz:* distilled deionized water; rainwater; carbon acid (carbonated water prepared by bubbling carbon dioxide into distilled water and allowing for equilibration with the environment for 24 h); citric acid (representative aliphatic organic acid, commonly identified in soils); and salycyclic acid (a common, low molecular weight aromatic acid in soils). For the two organic acids, 10^{-2}, 10^{-3} and $10^{-4}M$ solution, of each were used. Thus there were two powdered rock types and nine leaching solutions, and the experiment was replicated three times while the whole experimental set up was kept in the laboratory (temperature range 25-31°C) which approximates the natural humid tropical environmental conditions with regards to temperature. The experimental temperature was equivalent to the laboratory room temperature throughout the duration of the leaching period. The rainwater used was also analysed and the leachate obtained from the introduction of rainwater used was corrected for the elemental content of rainwater used. The leaching solutions were introduced into the sample chamber through the irrigation system, using 20 ml of the leaching solution at a time to maintain a 1:1 (w/v) sample: solution ratio throughout the period of leaching.

The powdered rock sample and leaching solution were allowed to equilibrate for 24 h following irrigation after which the drainage system was adjusted by opening the small perforation plugged with rubber cork to allow the leachate to drain off. The drainage system was normally left opened for 48 h before the sample was re-irrigated. This was to simulate reducing (ponding) and oxidizing (air-filled macropore condition) as suggested by Rose *et al.* (2000), who also indicated that intermittent leaching can improve leaching efficiency (see p. 891, Rose *et al.*, 2000). Leachates were kept in plastic containers and the experiment was run for 10 weeks. Leachates were analysed for Ca, Mg, Fe and Al by AAS although the concentrations of Fe and Al in the leachates were below the detection limits (0.001 mg/

1) of the instrument. The K and Na were determined by flame photometry and Si was colorimetrically determined using the ammonium molybdate blue method (Kilmer, 1965). Mean values obtained from the three different concentrations of the organic acid leachates were reported. The actual amount of elements extracted by successive effluents and the actual volumes of successive effluents were computed. Cummulative amounts extracted were calculated and plotted against the cumulative volumes of leachate. The mobility sequence (i.e. the ease by which the elements were leached) of the extracted elements was also examined.

Results and discussions

The results of the leaching experiment carried out over a period of 10 weeks are presented in Table 2. Of the five leaching solutions under the same laboratory room temperature (27-31 °C) and pressure conditions, distilled deionized water with the highest *p*H and, therefore, least hydrogen ion concentration [H^+], appears to be the least effective in leaching out the basic cations, but most effective in leaching out silica (Table 2). Rainwater with an average *p*H of 5.80 (Table 2) appears to be as effective in causing hydrolytic weathering in these rocks as carbonated water, which represents a weak inorganic acid. At the level commonly present in tropical soils, the organic acid representatives chosen were as effective as acidic precipitation or carbonated water in leaching out the basic cations and silica. It can, therefore, be suggested that the *p*H of the leaching medium has a pronounced influence on the effectiveness of the solution in causing hydrolytic reaction. Manley & Evans (1986) similarly noted that elemental release in simulation weathering is significantly correlated with the *p*H of the solution. At the concentrations employed, the effectiveness of the representative aliphatic organic(citric) acid employed is slightly higher than that of the aromatic

TABLE 2

Total elemental release from granite-gneiss over 10 weeks of leaching

Leaching solution	*Leachate composition (g/kg sample)*					
	p*H*	*Ca*	*Mg*	*Na*	*K*	*Si*
Coarse grained granite-gneiss						
Distilled water	6.80	4.477	1.948	11.43	17.00	4.73
Rain water (*p*H 5.14 - 6.45)	5.80	5.676	2.731	11.34	14.32	4.21
Carbonated water	5.60	8.362	4.218	16.86	20.82	4.16
Citric acid solution	5.60	9.815	4.009	26.52	23.30	4.92
Salycyclic acid solution	5.40	6.931	3.242	22.94	18.59	4.95
Medium grained granite-gneiss						
Distilled water	6.80	2.096	5.493	8.81	14.24	6.80
Rain water (*p*H 5.14 - 6.45)	5.80	8.410	6.464	56.88	24.43	6.54
Carbonated water	5.60	9.899	6.155	15.10	19.26	3.43
Citric acid solution	5.60	7.340	11.000	115.79	45.03	4.79
Salycyclic acid solution	5.40	9.624	6.452	13.46	26.32	7.53

(salycyclic) acid member in ehancing hydrolytic weathering of the rock. This indicates that the strength or *p*H of an organic acid is not the only factor determining its effectiveness in causing rock and mineral weathering.

The chelating ability and ionization constant of the acid were suggested (Boyle *et al.*, 1974) as other factors which enhance the ability of an organic acid in mineral weathering. The pattern of elemental release in both rock types by the individual leaching solutions appears to be similar. However, slightly more Mg and Ca were leached from the medium-grained granite gneiss than from the coarse-textured equivalent by the different leaching solutions (Table 2). From Table 3, the medium grained granite-gneiss has slightly more MgO (0.72-1.65%) and CaO (0.25-0.51%) than the coarse grained equivalent. The probable reason may be due to the slightly higher content of these elements (Mg and Ca) in medium-grained than coarse-textured granite-gneiss.

A plot of the cumulative amount of elements extracted against cumulative volumes of different leaching solutions is shown in Fig.1 (i-x). This is with a view to providing an estimate of total amount extractable by this technique. Most of the curves are positively curvilinear, indicative of increases in the quantity of elements leached with higher cumulative volume of leachates. Therefore, it may be suggested that the higher the magnitude of leaching, the greater the amount of these elements that will be leached. The curvilinear shape of the curves indicates that the total volume of leachate used was probably not sufficient as to almost completely leach out all of these extractable elements. Curves which tend towards asympotic values indicate the total amount extractable (Sehgal *et al.*, 1972). By considering the total amounts of each element extracted and the total volumes of solution, each as 100%, the cumulative amounts and cumulative volumes were expressed in percentages. This representation (Fig. 2i-x) is indicative of the relative ease with which different elements were leached during the experiment.

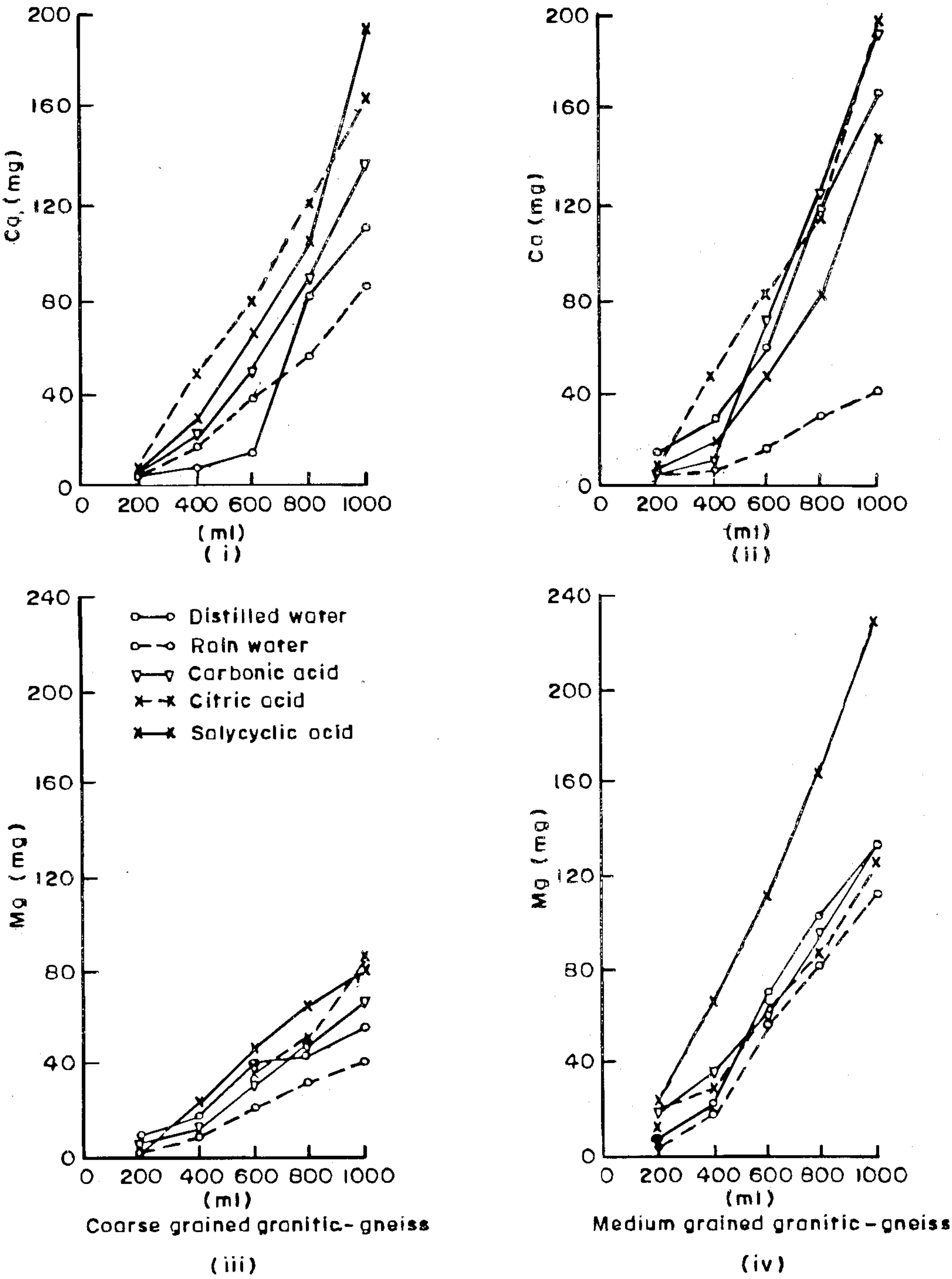
From the plot, Mg, K and Na show almost equal mobilty with the different leachates

TABLE 3

Chemical and mineralogical composition of the granite-gneiss from different locations in South-western-Nigeria

Rock type	*No. of samples (n)*	*Elemental composition (%)* SiO_2	Al_2O_3	Fe_2O_3	MgO	K_2O	CaO
Coarse textured	3	68.80	16.19	3.26	1.23	4.18	0.53
	4	67.50	17.23	2.22	0.90	3.82	0.35
Medium grained	4	72.00	15.49	3.03	1.65	5.25	0.25
	3	73.17	16.52	3.22	0.72	3.75	0.51
		Mineralogical composition (%) *Quartz*	*Plagioclase*	*Biotite*	*K-Feldspar*	*Muscovite*	
Coarse textured		40	38	13	6	1	
Medium grained		48	29	15	6	0.1	

n = number of rocks samples analysed per location



(i)

(ii)

Coarse grained granitic-gneiss

(iii)

Medium grained granitic-gneiss

(iv)

Fig. 1(i-iv). Cumulative amount of elements extracted by corresponding cumulative volumes of different leaching solutions.

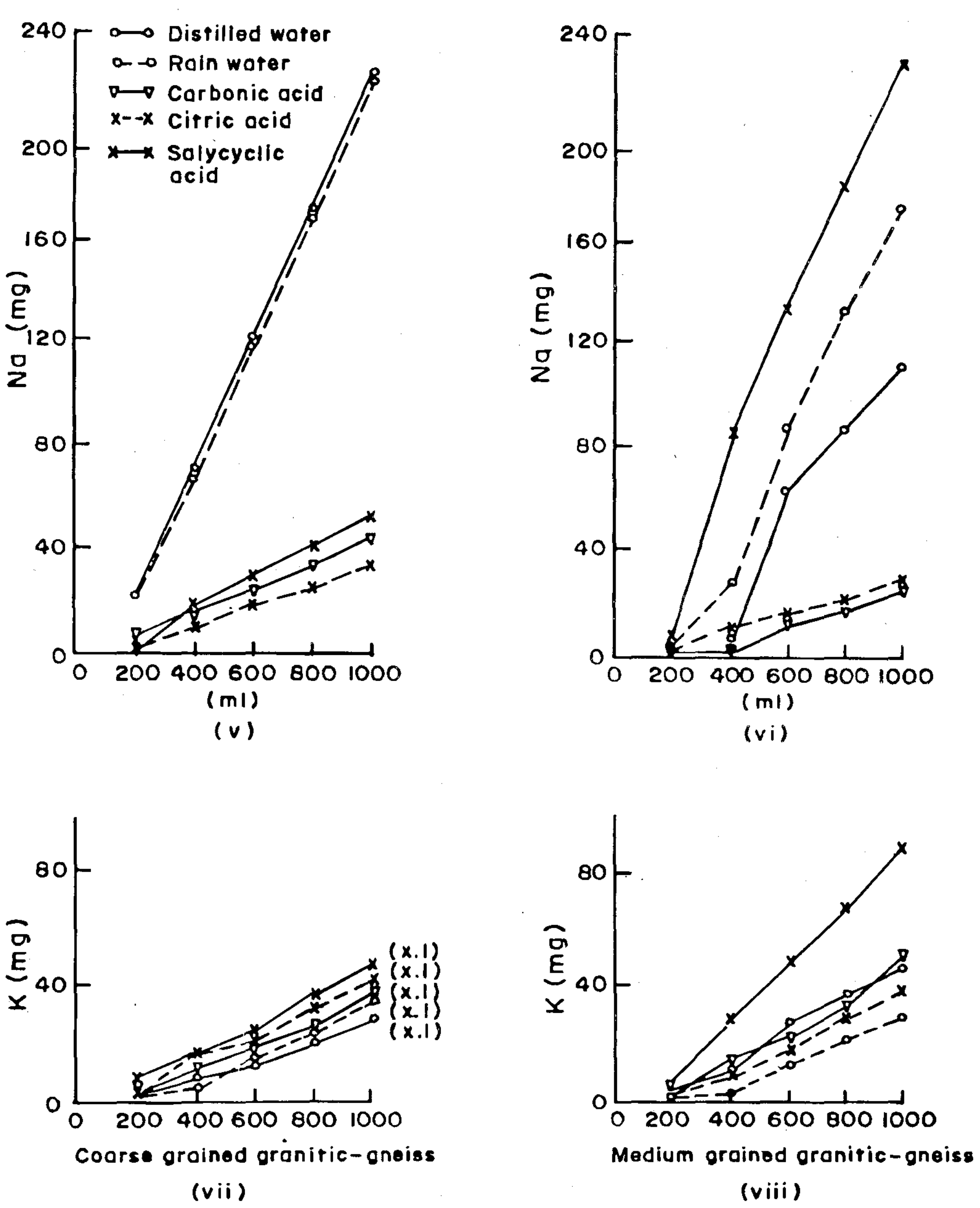


Fig. 1(v-viii). Cumulative amount of elements extracted by corresponding cumulative volumes of different leaching solutions.

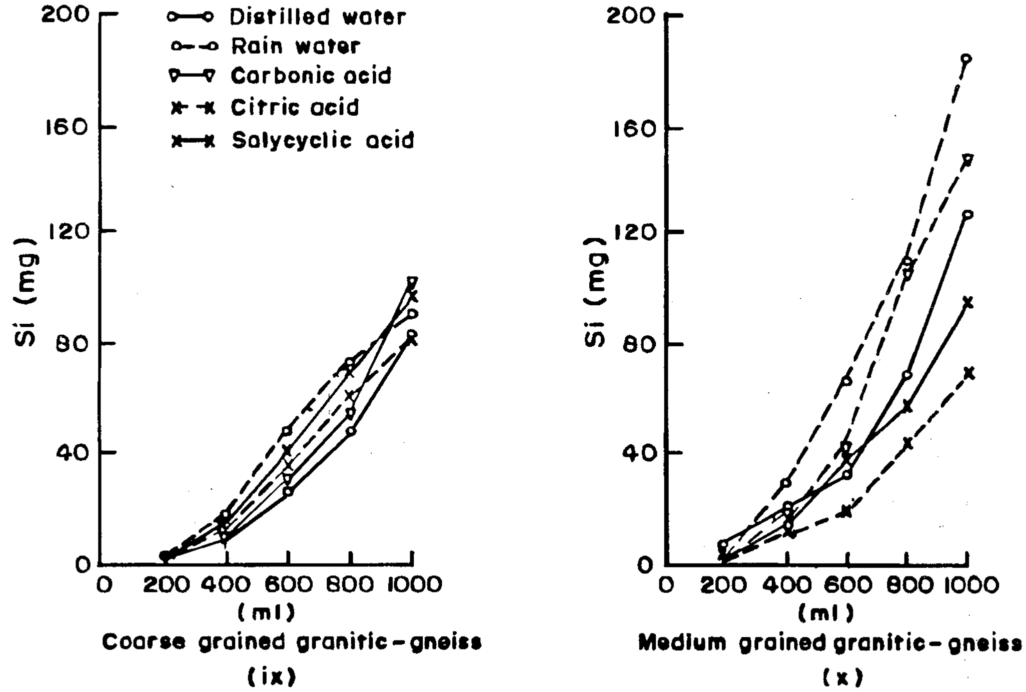


Fig. 1(ix-x). Cumulative amount of elements extracted by corresponding cumulative volumes of different leaching solutions.

(Fig. 2 i-vi). For these elements, about 80% of the total extracted were leached with 80% of the cumulative volume of leachates. However, only about 45-65% of the total extracted Si were leached with 80% cumulative volume of the leaching solutions (Fig. 2 vii and viii). Calcium is slightly more moblie than Si because between 54-75% of the total extracted were leached with 80% cumulative volume (Fig. 2 ix and x), but slight less mobile than Na, K, and Mg, where about 80% of the total extracted were leached by 80% cumulative volume. Sehgal *et al.* (1972) reported an average mobility sequence of Na>Mg>Ca>K>SiO_2 in Ustic soils. In their study, the relative immobility of K was thought to be due to its selective rentention by living matter or crystal lattices. However, in this study, Na~Mg~K>Ca>SiO_2 and since K appears to be more mobile than Ca, it is, therefore, suggested that at the initial stage of weathering under humid tropical conditions with particular reference to southwestern Nigeria, there is leaching out and elimination of SiO_2, alkali and akaline earths through hydrolytic weathering of the primary minerals.

Inspite of the presence of Fe (2.22-3.26% Fe_2O_3) and Al (15.49-17.23% Al_2O_3) in the original rocks that were leached (Table 3), only traces of Al and Fe were detected in the leachates even with the very dilute organic acids as the leaching solutions. The very low concentration of Al and Fe in the leachates is probably indicative of low mobility (i.e. high retention) of these elements at the initial stage of weathering and soil development. This may suggest accumu-

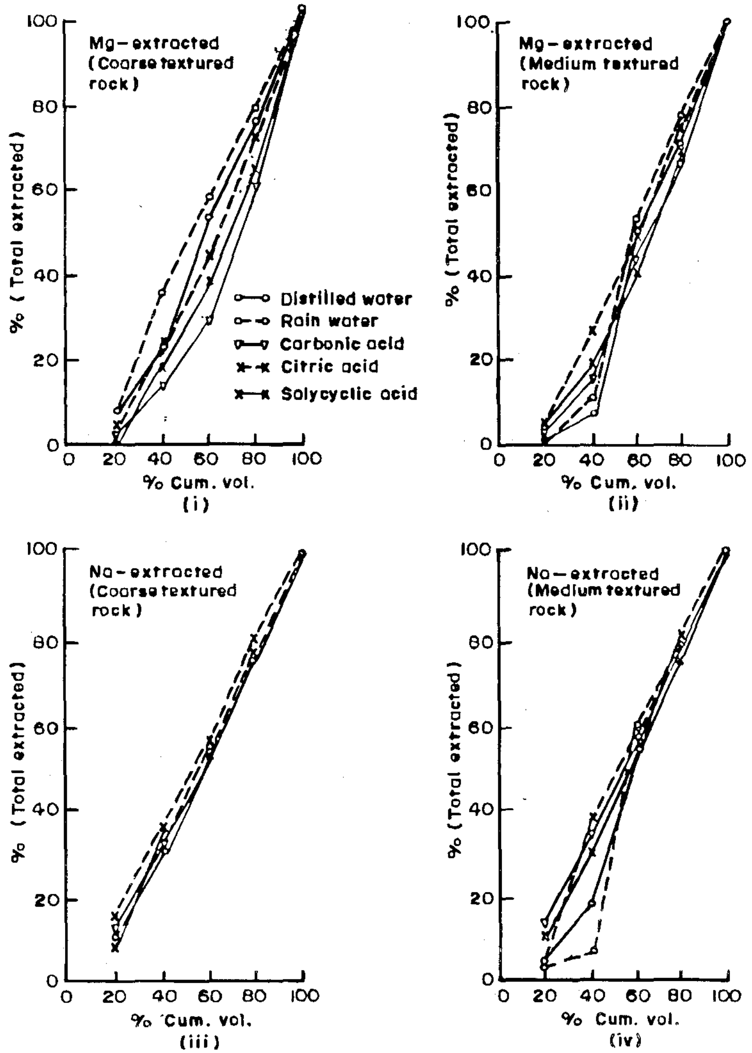


Fig. 2(i-iv). Cumulative percentage of element extracted vs corresponding cumulative volume of different leaching solutions.

lation of Fe and Al in the residue left after leaching. The morphological characteristics of the modal soil profiles (Table 4) clearly indicated residual accumulation of Fe and Al judging by the Hue recorded. These observations are in line with those of Sehgal *et al.* (1972) and Tessens & Shamshuddin (1982) who noted that ferrallitic weathering is the dominant pedogenetic process in the humid tropical region, and that the process is characterized by a residual accumulation of Fe and Al oxides, a total leaching of the bases and appreciable loss of silica.

The factors which appear to have encouraged hydrolytic weathering in the region include relatively high rainfall, most of which fall within 6-7 months of the year (Table 1), a relatively high soil temperature throughout the year [isohyperthermic soil temperature], acidic precipitation and the

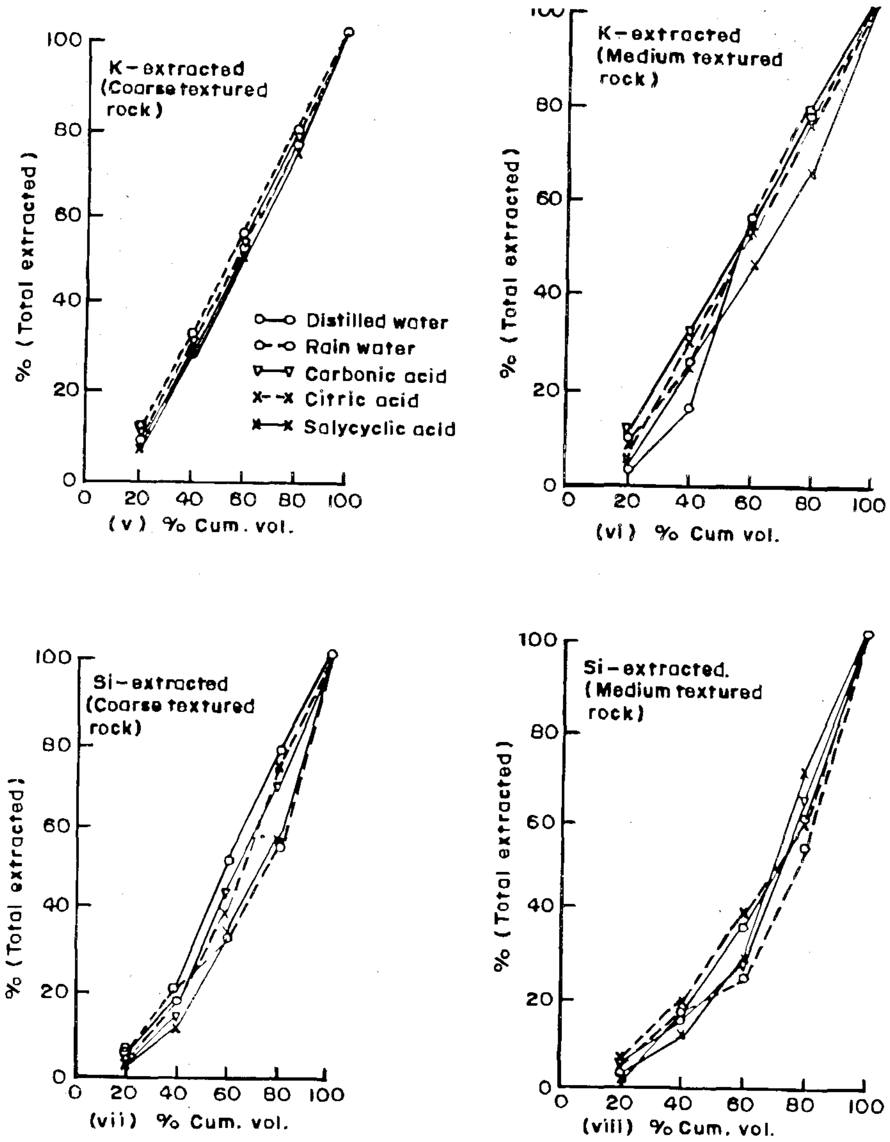


Fig. 2(v-viii). Cumulative percentage of element extracted vs corresponding cumulative volume of different leaching solutions.

low content of the basic cations of the parent rock (Table 2 and 3). The rainfall quantity, intensity and distribution create a condition whereby the precipitations is far greater than 0.8 of potential evapotranspiration (PET), regarded as the lower threshold value of soil moisture adequacy (Virmani, 1976). Consequently, leaching of the basic cations and silica is greatly encouraged since the lower threshold value of soil moisture adequacy is exceeded (Virmani, 1976) between April and October (Table 1). The high soil temperature (27-31°C at 50 cm soil depth (Table 1)

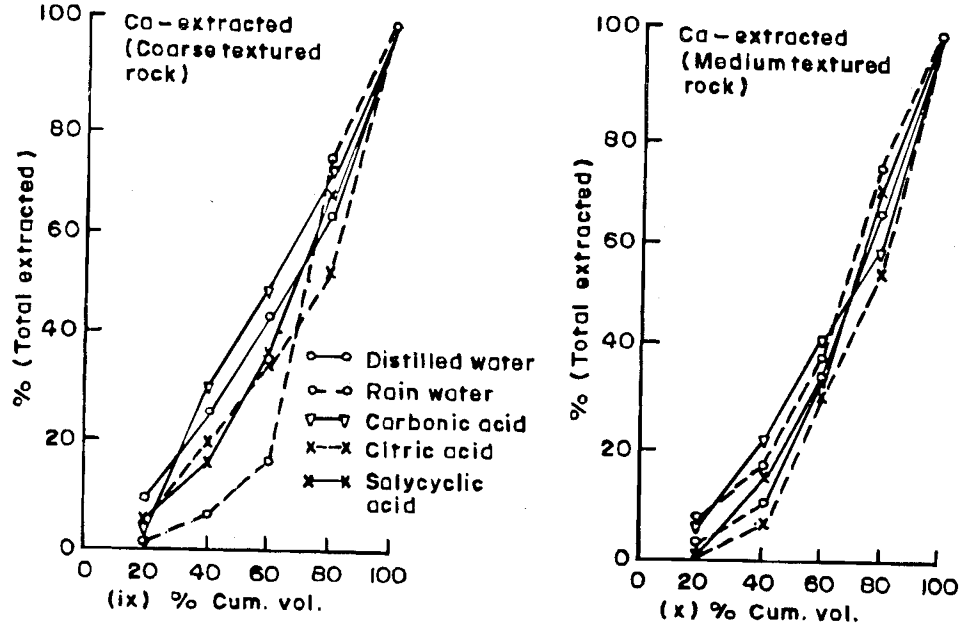


Fig. 2(ix-x). Cumulative percentage of element extracted vs corresponding cumulative volume of different leaching solutions.

encourages photolysis or dissociation of soil water, leading to a build-up of hydrogen ions or a lowering of the *p*H of the soil solution (Buol *et al.*, 1997). This enhance rapid hydrolytic weathering of silicate minerals (Jackson, 1964). Siever (1962) also reported that high temperature and extreme leaching in general favour rapid desilication and accumulation of iron, immobilized in ferric oxide forms under oxidizing conditions. The acidic precipitation (rain water *p*H 5.14 - 6.45) in the area is believed to furnish additional source of H^+ thereby intensifying hydrolytic weathering. This is further encouraged by the acidic parent rock with low content of basic cations (Table 3), and, further more, the upland area of south-western Nigeria is also well drained (Ojanuga, 1978). Therefore, it appears that the climatic, geologic and physical settings of the region naturally predispose the rocks to ferrallitic pedogenesis.

Conclusion

The effects of intensive leaching of granite-gneiss by the tropical rainfal, acidified carbonated water and simple aliphatic (citric) and aromatic (salycyclic) organic acids, at the onset of drock weathering, were investigated by simulated weathering for 10 weeks. The results indicated that, at the initial stage of weathering of granite-gneiss, more Mg and Ca were leached from the medium grained granite-gneiss than the coarse textured equivalent and that, in terms of relative ease with which the different elements were leached, Na~Mg~-K>Ca>SiO2, while Fe and Al concentrations in the leachates were below the detection limit (0.001 mg/kg). The presence of mostly acidic parent rock that are low in basic cations in an environment with acidic rain (rain water *p*H, 5.14 - 6.45), high annual rainfall (>1300 mm/yr) with greater than 0.8 PET and high soil temperature (27-31°C at

91-161	Btl	5 YR 5/8	7.5 YR 5/8	sligsc	3 msbk	ws	wp	-	5.6	gs	Patchy thin
161-197	Bt2	5 YR 5/8	2.5 YR 4/8	sligscl	3 msbk	wss	wp	-	5.3	ds	Partchy thi
197-217	BC	2.5 YR 4/6	7.5 YR 5/6	fgsc	3 csbk	was	wps	-	5.0	gs	Soeck of fe
217-301	CI	2.5 YR 4/6	7.5 YR 5/6	fgscl	3 csbk	wss	wps	-	5.0	ds	White spec weathered
301-339	C2	2.5 YR 4/8	10 YR 5/2	fgscl	3csbk	wss	wps	-	5.0	dw	Muscovite weathered
339-442	Cr	2.5 YR 4/8	10 YR 5/2	gscl	massive	wss	wps	-	5.0	-	Prominent structure, m
					Two series (Profile 2IT)						
0-2	A	5 YR 3/2	-	goscl	1 fgr	wso	wpo	cf	5.8	gs	-
20-40	AB	7.5 YR /4	-	gscl	2 msbk	wss	wps	cm (co)	5.5	cs	Abundant q
40-85	Bt1	5 YR 4/6	-	gsc	2 msbk	ws	wp	Ff	5.0	ds	Common q patchy thin
85-130	Bt2	5 YR 4/8	-	gsc	3 mc sbk	wvs	wvs	Fr	5.1	gs	Thin cutans and stones
130-180	Bt3	2.5 YR 4/8	10 YR 4/8	sligscl	3 msbk	ws	wp	-	5.1	ds	Partchy thi
180-260	BC	2.5 YR 4/8	7.5 YR 3/8, 10 YR 6/6	scl	3 mc sbk	wss	wps	-	5.0	ds	-
260-310	C	2.5 YR 4/8	7.5 YR 6/8, 2.5 YR 6/2	cosl	3 csbk	wso	wpo	-	5.2	ds	Abundant m and white
310-415	Cr	2.5 YR 4/8	2.5 YR 6/2; 7.5 YR 6/8	lcos	massive	wso	wpo	-	5.1	-	(N8/rottene

											thin cutans
108-160	Bt1	2.5 YR 4/6	10 YR 6/6; 7.5 YR 3/8	sc	3 msbk	wvs	wvp	-	6.3	gs	Patchy thin to thick cutans; fe
160-240	Bt2	5 YR 4/6	10 YR 5/8; 10 YR 4/8	c	3 csbk	wvs	wvp	-	6.1	dw	Few patchy t
240-350	C	5 YR 4/6	10 YR 5/8; 10 YR 4/8	sli sc	massive	wvs	wvp	-	6.1	ds	Few flaskes o feldspar
350+	Cr	5 YR 4/6	19 YR 6/6; N8/	sc	massive	-	-	-	5.2	-	Abundant w patches
					Ondo series (Profile 4-1)						
0-20	A	10 YR 3/3	-	sligcosl	1fgr	wss	wps	cf(m)	7.0	gs	-
20-28	BA	10 YR 3/4	-	fgsc	2 msbk	ws	wp	cm(co)	6.5	cs	Quartz fragm
28-110	Btc	7.5 YR 5/6	-	gc	3 msbk	wvs	wvp	Ff	6.4	ds	Partchy thin nodules and q
110-140	Bt	7.5 YR 5/6	5 YR 4/6	slifgsc	3mc	wvs	wvp	-	6.4	ds	Patchy thin c quartz gravels
140-186	BC	7.5 YR 6/8	2.5 YR 4/8; 10 YR 7/3	sligsc	massive	wvs	wvp	-	6.2	ds	*-ditto-*
186-273	Cr	7.5 YR 6/8	7.5 YR 5/6; 10 YR 7/8	slifgsc	massive	-	-	-	5.4	-	Abundant whi patches

Abbreviations Texture: sli= slightly; f = fine; s = sand; c = clay; l = loam; co = coarse;
Structure: 1 = weak; 2 = moderate; 3 = strong; f = fine; m = medium; r = crumb; gr = granular; sb = subangular blocky
Consistence: w = wet; ss = slightly sticky; s = sticky; vs = very sticky; sp = slightly plastic; p = plastic; vp = very plastic;
Roots: c= common; m = medium; f= fine; co= coarse; f= few.

50 cm soil depth) are the factors that are considered to enhance hydrolytic weathering in the region. The hydrolytic weathering and the climatic, geologic and physical setting of the region appear to predispose the rocks to ferrallitic pedogenesis.

References

Boyle, J. R, Voigt, G. K. & Sawhney, B. L. (1974) Chemical weathering of biotite by organic acids. *Soil Sci.* **87**, 42-45.

Buol, S. W., Hole, F. D., McCraken, R. J. & Southard, R. J. (1997) *Soil genesis and classification* (4th edn). Ames, Iowa.: Iowa State University Press. 527 pp.

Eswaran, H. (1979) The alteration of plagioclases and Augites under differing pedo-environmental conditions. *J. Soil Sci.* **30**, 347-555.

Henin, S. & Pedro, G. (1965) The laboratory weathering of rocks. In *Experimental Pedology* (E. G. Hallsworth and D. U. Crawford, eds), pp. 29-39. Lodon: Buterworths.

Jackson, M. L. (1964) Chemical composition of soils. In *Chemistry of the Soil* (F.E. Bear, ed.), pp. 71-134. New York: Reinhold Publishing Corporation.

Keay, R. W. J. (1949) *An outline of Nigeria vegetation,* 1 edn. Lagos: Government Printer. 157 pp.

Kilmer, V. J. (1965) Silicon. In *Methods of soil analysis II* (C. A. Black, ed.), pp. 595-962. Agronomy **9** (2). Madison, U. S. A.: American Society of Agronomy.

Manley, E. P. & Evans, L. J. (1986) Dissolution of Feldspars by Low-Molecular Weight Aliphatic and Aromatic acids. *Soil Sci.* **141** (2), 106-112.

Millot, G. (1970) *Geology of clays.* New York: Springer Verlag. 429 pp.

Ojanuga, A. G. (1978) Genesis of soils in the Metamorphic Forest Region of Southwestern Nigeria. *Pedologie XXVIII* **1**, 105-117.

Ojo-Atere, J. A., Olomu, E. I., Fagbami, A., Omueti, J. A. & Fapohunda, A. (1987) Environment of Southwestern Nigeria. In *A review of soils and fertilizer use research in southwestern Nigeria.* Lagos: Fertilizer Procurement and Distribution Department, Federal Ministry of Agriculture, Water Resources and Rural Development. 312 pp.

Rahaman, M. A. (1988) Recent advances in the study of the basement complex of Nigeria. In *Precambrian Geology of Nigeria,* pp. 11-41. Kaduna: Geological Survey of Nigeria. (Esho Printers Ltd).

Rose, D. A., Adey, M. A. & Al-Sobai M. (2000) Laboratory experiments and modelling studies of leaching of intermittently drained columns. *Aust. J. Soil Res.* **38**, 891-903.

Sehgal, J. L., Gombeer, R. & D'Hoore, J. (1972) Induced migration of clay and other moderately mobile soil constituents. IV. Mobility of sodium, magnesium, calcium, potassium and silica in some Indian soils subjected to perfusion with water under slightly unsaturated conditions. *Pedologie XXIII* **3**, 255-283.

Siever, R. (1962) Silica solubility, 0-200 °C and the diagenesis of silieceous sediemnts. *J. Geol.* **70**, 127-150.

Smyth, A. J. & Montogmery, R. F. (1982) *Soils and Land-use in Central Western Nigeria.* Ibadan: Western Nigeria Government Press. 217 pp.

Tessens, E. & Shamshuddin, J. (1982) Characteristics related to charge in Oxisols of Penninsular, Malaysia. *Pedologie XXX11* **1**, 85-106.

Virmani, S. M. (1976) *The agricultural climate of Hyderabad region in relation to crop planning-a sample analysis.* Hyderabad, India: ICRISAT. 54 pp.

Wahlstrom, E. E. (1960) *Petrographic mineralogy.* New York: John Wiley and Sons Inc. 407 pp.