THE CHEMISTRY OF SOME BRAZILIAN SOILS: ELEMENT MOBILITY DURING INTENSE WEATHERING

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ABSTRACT

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Chemical data for 56 elements in soils from three regions of Brazil (Bahia, Amazon, Goias) indicate that intense chemical weathering leads to a product soil essentially in the system, $\text{SiO}_2\text{--Al}_2\text{O}_3\text{--Fe}_2\text{O}_3\text{--H}_2\text{O}$. The major minerals of the leached soils are quartz, kaolinite, gibbsite, goethite and hematite.

Trace elements show a wide range of behaviour from those which are enriched as for some bio-important elements (B, Cl, Mo, Se, Sn, I) and refractory metals (Sc, Zr, Nb, Gd, Tm, Th) to the majority which are severely leached. Trace-element behaviour appears to be largely controlled by the dominant clay or $\text{Al}_2\text{O}_3\text{--SiO}_2$ minerals, or the degree of weathering.

Consideration of the chemistry of lateritic soils and groundwaters indicates that the development of deep lateritic profiles requires times in the order of tens of millions of years in a very stable continental setting.

INTRODUCTION

Chemical weathering of rocks is one of the major processes which modifies the earth's surface and is one of the most important factors in the geochemical cycle of the earth. While weathering is controlled by many variables, the importance of the process can be appreciated when it is noted that river water contains in the order of 120 ppm dissolved mineral material of which over 50% is rock derived; we also know that the time constants of mineral solution processes are very short. At 100 ppm dissolved mineral material, then for 1 m of rain per year, the land surface is removed at about 1 ton $\text{ha}^{-1} \text{yr}^{-1}$ or elevation is removed at a rate of 50 m per million years.

Chemical weathering involves a number of simple well-defined processes; congruent and incongruent solution, hydration and oxidation reactions. Many of the observed phenomena may result from the influences of biological processes and biological debris. It is well known that organic species such as proteins (Blundell and Jenkins, 1977) are powerful complexing reagents for a wide range of metallic elements.

Normally, the first stage of weathering results in the formation of complex smectite clays (illite—montmorillonite, etc.). These clays are well known to be highly active ion-exchange species. More continued weathering leads to kaolinite—quartz assemblages and eventually, as silica activity falls, phases such as gibbsite, goethite—hematite. As these latter phases develop, ion-exchange and ion-retention processes diminish because of the reduction in the cation-site complexity of the phases. In general, many of the processes follow common knowledge of the solubility of parent oxide phases; removal of alkali and alkaline earth cations, retention of Al, Ti, Th, etc. But the behaviour of some elements necessitates consideration of biological processes or of aerosol input into the environment. Recently, Dennen and Norton (1977) have described the chemistry of some Amazon bauxites. General descriptions of tropical weathering are found in Marbut and Manifold (1926), Mohr and Van Baren (1954), Nye and Greenland (1960), Ollier (1969) and Buringh (1970). Here we will concentrate on the more common kaolinite-type soils.

While detailed knowledge of the weathering process is required for many aspects of environmental science from agriculture to nuclear-waste disposal, detailed knowledge is still relatively scarce (see Keller, 1962; Wedepohl, 1969). Here we wish to present a selection of data for a wide range of elements from studies in Brazil. More extensive data can be provided on request (Kronberg, 1977).

SAMPLING AND LOCATIONS

Soil samples were collected from three regions of Brazil (Fig. 1). The material studied is representative of the products of intense chemical weathering. The weathering histories of the regions appear variable. Some samples collected obviously represented weathering in situ, as primary rock structures and textures are preserved (Fig. 3). At the other extreme are some highly weathered gibbsitic soils overlying a land surface which may have undergone several cycles of erosion and uplift. Characteristic differences among the samples from the three regions considered here are shown by the dominant soil mineralogy, which is used as a variable to which trace-element concentrations can be related.

Samples were obtained from the following regions:

(a) *Bahia region.* In Bahia State samples were taken west of Salvador from surface soils developed on Cretaceous sediments, and from profiles near Ilheus where the weather cover is deep and highly leached. At the latter site occasional outcrops indicate syenitic—migmatitic source rocks (see Table I).

(b) *Amazon region.* Samples are from deep profiles along the Trans-Amazon Highway about 150 km north of Marabá in Maranhão State. The depth of chemical weathering is extraordinary (~ 100 m); however, textural and structural remnants indicate granulitic—gneissic terrain (Figs. 2 and 3).

Fig. 1. Sketch map of Brazil indicating sample collection sites.

Fig. 2. Typical scenery along the Trans-Amazon Highway. There are virtually no unweathered rocks and hence construction is difficult.

TABLE I

Sample description

Bahia region		Amazon region	
sample	description	sample	description
FB 75-8	A horizon	FA1	soil in root system of large uprooted tree
FB 75-9	B horizon of FB 75-8	FA4	weathered feldspathic pegmatite, 8 m below surface
FB 75-10	B horizon, 1 m below FB 75-8		
FB 75-11	6 m below surface	FA5	surface, forest soil
FB 75-12	weathered syenite	FA6	B horizon of FA5
FB 75-13	C horizon	FA7	10 m below FA5
FB 75-14	C horizon	FA8	15 m below FA5
FB 75-15	partially altered rock	FA9	19 m below FA5
FB 75-16	3 m below surface		
FB 75-17	B horizon	FA10	forest top soil
FB 75-18	A horizon of FB 75-17	FA11	B horizon of FA10
FB 75-19	soil trapped in tree root	FA12	lateritic concretions below FA11
		FA13	12 m below FA10
SB 1	soil from coco grave		
SB 2	soil from sugar cane field	FA14	top soil, burnt forest, 3 yr. old
SB 3	soil from orange grove		
SB 4	soil from pasture land		
SB 5	soil from pineapple plantation		
BL	Barnes Loam, South Dakota

Fig. 3. Typical metamorphic structures preserved in a deeply weathered Amazon profile. These rocks have K contents of less than 0.1%, Ca and Mg in the parts per million level.

TABLE II
Mineralogy

Sample	Quartz	Kaolin- ite	Gibbs- ite	Goe- thite	Hema- tite	Ilmen- ite	Il- lite	Plagio- clase	Other
<i>(a) Bahia region:</i>									
FB75-8	m	m		t	t	m			t
FB75-9	m	m		t	t	m			t
FB75-10	m	m							
FB75-11	m	m					m		
FB75-12	m	m					m	t	t
FB75-13	m	m			t		m		t
FB75-14	m	m			m		m		t
FB75-15	m	m			t	t	t	t	t
FB75-16	m	m			t	t	t		t
FB75-17	m	m			m	t			
FB75-18	m	m			m	t			
FB75-19	m	m		m		t			m
SB1	m	m							Mon
SB2	m								Mt
SB3	m	m							m
SB4	m	m		m	m	m			
SB5	m	m		t	t	t			m
<i>(b) Amazon region:</i>									
FA1	m	m		m		t			
FA4	m	m		t					
FA5	m	m		m					
FA6	m	m		m					
FA7	m	m		m					
FA8	m	m		m					
FA9	m	m		m					
FA10	m	m		m					
FA11	m	m		m					
FA12	m	m		m	m				
FA13	m	m		m	m				
FA14	m	m		m					
<i>(c) Goias region:</i>									
75-1A	t	t	m		m				
75-1B	m	t	m		m				
75-2A	m	t	m						
75-2B	m	t	m		t				
75-3A	m	t	m						
75-3B	m	t	m						
75-4A	m	t	t						
75-4B	m	t	t						
75-5A	m	t	m						
75-5B	m	t	m						
75-6A	m	t	m						
75-6B	m	t	m						
75-8A	m	t	m		t				
75-8B	m	t	m		t				
75-9A	m	t	m		m				
75-9B	m	t	m		m				

m = major constituents; t = trace constituent.
Mon = montmorillonite; Mt = magnetite.

TABLE III

Soil analyses (wt.%)

Sample	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	MgO	CaO	Na ₂ O	K ₂ O	P ₂ O ₅	MnO	TiO ₂
<i>(a) Bahia region:</i>										
FB75-8	63.5	7.23	11.4	0.19	0.30	0.10	0.10	0.10	0.19	3.90
FB75-9	42.2	21.6	12.6	0.46	0.30	0.10	0.15	0.10	0.10	1.11
FB75-10	46.2	28.5	6.95	0.50	0.03	0.10	0.10	0.01	0.01	0.32
FB75-11	37.4	18.9	20.9	3.08	0.10	0.10	0.11	0.11	0.31	2.71
FB75-12	70.8	19.0	2.23	0.15	0.86	0.43	0.88	0.10	0.10	0.16
FB75-13	65.9	15.0	5.17	3.00	0.30	0.10	2.05	0.10	0.10	0.66
FB75-14	47.2	20.8	7.52	0.92	0.30	0.10	0.74	0.10	0.10	0.72
FB75-15	54.1	18.5	10.3	3.28	6.13	3.12	1.76	0.30	0.21	0.74
FB75-16	58.1	17.6	5.07	0.69	0.30	0.10	1.57	0.10	0.11	0.41
FB75-17	64.4	17.7	5.22	0.12	0.30	0.10	0.30	0.03	0.30	0.44
FB75-18	57.2	16.3	11.0	0.10	0.10	0.05	0.10	0.10	0.14	2.30
FB75-19	54.8	16.8	8.78	0.04	0.10	0.05	0.10	0.03	0.01	1.28
SB1	88.6	0.98	0.50	0.14	0.22	0.03	0.10	0.10	(0.003)	0.16
SB2	46.0	11.6	6.93	1.59	0.72	0.10	1.31	0.13	0.27	0.97
SB3	87.8	3.83	1.20	0.04	0.10	0.03	0.10	0.06	(0.003)	0.61
SB4	58.6	14.0	9.97	0.04	0.17	0.03	0.10	(0.006)**	0.01	1.69
SB5	78.4	8.62	2.22	0.01	0.10	0.03	0.10	0.02	0.01	0.69
<i>(b) Amazon region:</i>										
FA1	31.4	26.4	26.4	0.02	(0.003) ²	(0.003)	0.02	0.10	0.10	3.27
FA4	79.6	14.2	0.32	0.04	(0.003)	(0.003)	0.10	(0.005)	0.03	0.04
FA5	36.7	20.6	18.8	0.02	(0.003)	(0.006)	0.03	0.15	0.11	1.97
FA6	57.5	22.5	8.04	0.01	(0.001)	(0.003)	0.01	0.02	0.04	0.16
FA7	62.2	22.6	5.85	0.01	(0.004)	0.07	0.16	0.02	(0.004)	0.65
FA8	71.0	21.2	2.29	0.01	0.04	0.07	0.17	0.03	0.01	0.26
FA9	33.6	23.7	29.4	0.02	(0.003)	(0.002)	0.02	0.06	0.40	1.62
FA10	57.7	13.3	9.53	0.01	0.02	0.09	0.08	0.08	0.06	2.33
FA11	49.5	25.4	14.2	0.05	(0.005)	0.09	0.18	0.05	0.03	1.07
FA12	23.8	11.2	57.1	0.07	(0.005)	(0.003)	0.02	0.19	0.07	0.61
FA13	42.6	29.3	14.5	0.12	0.02	0.09	0.29	0.05	0.05	0.94
FA14	78.2	9.65	3.04	0.06	0.01	(0.008)	0.17	0.04	0.02	0.51

(c) *Goias region:*

75-1A	24.8	29.9	12.1	0.14	0.01	0.01	0.05	0.06	(0.001)	1.77
75-1B	21.5	30.4	11.8	0.04	0.01	0.01	0.02	0.02	(0.003)	1.81
75-2A	15.4	34.2	13.8	0.13	0.01	0.03	0.76	0.02	(0.001)	1.85
75-2B	13.0	36.2	15.6	0.42	0.01	0.03	0.84	0.06	(0.003)	2.24
75-3A	18.4	45.6	1.04	0.04	(0.004) ²	0.03	0.06	(0.006)	(0.001)	2.86
75-3B	16.5	46.0	0.98	0.02	(0.004)	0.01	0.02	(0.002)	(0.0004)	2.83
75-4A	48.6	15.2	2.61	0.14	0.04	0.09	2.34	0.09	(0.001)	0.82
75-4B	55.4	18.9	3.85	0.42	0.01	0.06	3.00	0.06	(0.001)	0.99
75-5A	10.0	37.9	13.6	0.14	(0.004)	0.03	0.27	0.06	(0.001)	2.24
75-5B	10.5	39.8	16.4	0.04	(0.004)	0.03	0.30	0.02	(0.001)	2.35
75-6A	85.0	6.22	2.61	0.02	0.01	(0.003)	0.19	(0.006)	(0.0004)	0.38
75-6B	81.4	7.23	2.93	0.04	0.01	(0.003)	0.24	(0.006)	(0.001)	0.42
75-8A	24.3	31.1	12.1	0.04	0.01	0.01	0.07	0.06	(0.001)	1.87
75-8B	24.6	30.7	11.9	0.14	0.01	0.01	0.08	0.02	(0.003)	1.85
75-9A	22.6	37.7	11.2	0.04	0.01	(0.003)	0.01	0.02	(0.001)	2.29
75-9B	22.7	38.7	11.9	0.04	(0.004)	0.01	0.01	(0.006)	(0.003)	2.37
BL	69.3	11.3	3.84	0.92	1.61	1.14	1.80	0.17	0.16	0.49
Crust* ¹	58.5	15.8	6.50	4.57	6.51	3.06	2.22	0.25	0.14	1.05

*¹ Fairbridge (1972); *² mass spectroscopic data.

(c) *Goias region.* Near Brasilia, samples were taken from profiles at an experimental farm (Fazenda Aqua Limpa, Universidade de Brasilia), located within the Federal District. Residual soils predominate in the immediate area of Brasilia. These soils formed on a land surface, which may have developed in Cretaceous time.

In the three regions studied, a moderate to low relief prevails, and present-day rainfall ranges from 1000–2000 mm yr.⁻¹.

ANALYTICAL METHODS AND ACCURACY

Major and minor constituents were determined by standard X-ray fluorescence techniques (Norrish and Hutton, 1969). This information is reported on an unignited basis. Errors are considered to be in the 1% range for elements whose concentrations exceed 1%. Trace-element data were obtained by spark-source mass spectroscopy following normal semiquantitative procedures (J.A. James and J.L. Williams, in Waldron, 1959). Because of the procedure used, concentrations are estimated within a factor of 3, and thus a value of 10 $\mu\text{g g}^{-1}$ has bounds of 3–30 $\mu\text{g g}^{-1}$. The procedure gave satisfactory results on USGS standards (Flanagan, 1973).

MINERALOGY AND MAJOR-ELEMENT CHEMISTRY

In the Bahia region, the major minerals (Table II) besides quartz, are kaolinite and illite. Montmorillonite was confirmed in one sample. In some samples small quantities of primary minerals are present. Fe may occur as goethite or hematite, and Ti appears as ilmenite.

In the samples from the Amazon region, the major minerals are quartz and kaolinite. Gibbsite was not noted. Fe is present as goethite and sometimes hematite. Quartz and gibbsite are the dominant minerals in the samples from the experimental farm in Goias. Fe occurs here as hematite. The mineralogical differences suggest that the intensity of weathering varies for each sampling area and follows the order, Bahia < Amazon < Goias.

This pattern is borne out by the major-element chemistry (Table III). In Table III, (c) data for average crust (Fairbridge, 1972) and a fertile soil, Barne's Loam (BL), South Dakota (Bear, 1964) are included for comparison. The depletion of major elements is much greater in the samples from the Goias and Amazon regions than in the Bahia region. In the former regions over 95% of the macrochemical components can be accounted for by the assemblage, $\text{SiO}_2\text{—Al}_2\text{O}_3\text{—Fe}_2\text{O}_3\text{—H}_2\text{O}$. The sum of these oxides in the average $\text{Fe}_2\text{O}_3\text{—H}_2\text{O}$ composition is in the neighbourhood of 80%. TiO_2 may or may not concentrate. The oxides of Mn, P, Na, Mg, K and Ca tend to have consistently lower concentrations as the mineralogy shifts from more complex minerals (Bahia region) to the gibbsitic material (Goias region). In the Amazon and Goias regions the oxides of Na, Mg, K and Ca often have concentrations ($\sim 0.01\%$) 100-fold less than their crustal abundances.

These low concentrations are important to note when evaluating the agricultural potential of these soils. Na, Mg, K and Ca are included in the list of macronutrients, and on a good soil up to 50 kg ha^{-1} of these elements may be incorporated into the crops which are harvested. If the concentration level is 0.01%, then only 200 kg ha^{-1} of macronutrient would be present in a surface layer of soil 10 cm in thickness ($\rho = 2 \text{ g cm}^{-3}$). Obviously, these soils in their natural states cannot be long-range food producers. By comparison (BL, Table III, (c) in a temperate glacial soil, the concentrations of the oxides of Na, Mg, K, Ca are in the order of 1%, and there is a large reservoir of these nutrient elements in the glacial debris on which these soils have formed.

TRACE-ELEMENT CONCENTRATIONS

The trace-element information is shown in Table IV along with data for crustal abundances (Fairbridge, 1972) and soils (R.G. Mitchell, in Bear, 1964). Parent material was inaccessible due to the complexity of the weathering history (Goias region) and/or the depth of the weather cover.

The data have been divided into the following categories with respect to crustal abundance (CA) in Table V:

xe	= strongly enriched	10 CA	d	= depleted	0.1–0.3 CA
e	= enriched	3–10 CA	xd	= strongly depleted	0.01–0.1 CA
s	= stable	0.3–3 CA	xxd	= very strongly depleted	< 0.01 CA

Fig. 4. The common pattern of trace-metal retention as a function of clay mineralogy and time.

TABLE IV

Trace elements data ($\mu\text{g g}^{-1}$)

(a) Bahia region

Element	Crust ¹	Soil* ²	FB75-8	FB75-9	FB75-10	FB75-19	SB-1	SB-2	SB-3
B	9	10	0.5	2	5	2	5	50	5
F	544	100	470	>4500	470	470	30	100	100
S	340	1000	> 400	> 400	40	400	250	> 250	>250
Cl	126	1500	>5000	1500	5000	5000	50	150	>500
Sc	25		3000	100	100	300	30	100	30
V	136	100	400	130	100	10	10	100	10
Cr	122	120	500	50	50	50	20	50	5
Co	29	10	130	40	10	4	40	10	1
Ni	99	100	160	15	50	15	5	50	15
Cu	68	12	600	180	60	20	20	60	6
Zn	76	80	350	120	40	40	4	4	1
Ga	19	14	65	20	20	20	6	20	6
Ge	1.5		5	5	15	5	0.5	1	0.5
As	1.8	10	2	2	7	0.7	0.2	0.7	0.2
Se	0.05	1	0.3	0.3	0.3	0.4	0.1	0.1	0.1
Br	2.5		2	2	5	2	0.5	2	0.5
Rb	78	100	15	15	45	2	2	150	0.5
Sr	384	120	30	10	100	3	30	100	3
Y	31	50	10	10	10	10	5	10	1
Zr	162	400	2000	600	600	200	60	200	200
Nb	20		1300	135	400	40	5	15	5
Mo	1.2	1	3	30	30	1	1	1	1
Az	0.08		0.4	0.1	0.4	0.04	0.04	0.04	0.04
Cd	0.16		<0.1	0.1	0.1	<0.1	<0.1	0.1	0.4
Sn	2.1	5	8	25	80	8	8	8	8
Sb	0.2		2	7	7	2	7	20	2
I	0.46	4	30	90	30	10	1	10	1
Ca	2.6		0.3	0.3	1	0.3	0.3	10	0.3
Ba	390	800	700	200	700	200	70	200	7
La	34	50	85	25	85	25	8	25	0.7
Ce	66		55	55	160	55	15	55	5
Pr	9.1		2	7	70	7	1	2	0.2
Nd	40		9	30	90	9	3	30	1
Sm	7		<7	7	7	<7	2	7	2
Eu	2		2	0.5	2	<2	0.2	2	<0.2
Gd	6		7	2	20	2	0.7	7	<0.7
Tb	1		1	1	1	<1	0.1	1	<0.1
Dy			6	6	6	2	0.6	6	2
Ho	1		1	1	1	<1	0.3	0.3	0.3
Er	3.5		<4	4	120	<4	4	1	1
Tm	0.5		2	2	60	<0.6	0.6	0.6	0.6
Yb	3.1		3	3	3	<3	<3	3	<3
Hf	2.8		15	5	50	<5	<5	5	15
Pb	13	50	50	50	50	50	5	50	20
Th	8		20	60	60	60	2	0.5	
U	2.3		2	2	2	<2	<0.5	<0.5	0.5

*¹ Fairbridge (1972); *² Mitchell (see Bear, 1964).

SB-4	SB-5	FB75-11	FB75-12	FB75-13	FB75-14	FB75-15	FB75-16	FB75-17	FB75-18
15	5	2	15	15	15	5	15	15	5
> 250	10	470	>4500	>4500	>4500	1500	>4500	4500	470
> 250	250	40	> 400	> 400	> 400	40	> 400	> 400	400
> 500	500	1500	>5000	>5000	>5000	1500	>5000	5000	500
30	100	100	>3000	30	3000	30	300	1000	100
100	10	130	400	40	40	10	130	40	10
20	20	20	>1700	50	1700	50	50	20	20
4	1	40	130	40	20	40	40	4	10
50	50	50	50	50	50	5	15	5	15
60	6	600	180	60	180	60	180	60	60
1	1	120	3600	3600	360	120	40	10	40
6	6	20	2000	65	65	20	20	6	20
1	1	1.5	5	5	1	1	5	0.5	1
7	0.7	0.7	2	7	0.2	0.7	0.7	<0.2	0.7
0.1	0.1	0.1	0.1	0.3	0.3	0.1	0.1	<0.1	0.1
2	0.5	0.5	2	0.5	0.5	0.5	0.5	0.5	2
2	0.5	15	450	>4500	>4500	15	45	45	15
30	10	3	330	10	30	330	30	10	30
5	10	100	1	370	100	10	100	10	10
200	600	200	200	2000	850	2000	60	200	600
5	5	40	40	400	40	10	10	10	40
1	3	3	10	1	1	3	1	1	1
0.04	0.04	1	0.4	0.04	0.1	0.1	0.1	<0.04	0.04
<0.1	<0.1	0.1	0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
25	3	8	80	8	25	3	25	25	8
20	7	7	20	2	0.7	<7	7	0.7	0.7
30	3	3	10	1	10	1	30	3	30
1	1	1	1	100	100	1	10	3	3
20	20	700	6700	2000	6700	2000	2000	200	200
8	3	25	250	850	250	25	250	25	25
15	15	55	1800	540	250	180	180	55	180
2	0.7	20	20	200	100	7	70	7	7
3	3	30	90	870	300	30	90	30	30
2	7	20	70	200	70	20	70	7	7
0.2	0.6	7	7	70	7	7	7	0.7	0.7
0.7	2	20	20	70	20	7	20	7	2
0.1	0.3	3	10	10	10	3	10	1	<1
2	2	6	20	600	20	6	20	6	2
0.1	1	3	3	10	3	3	10	1	<1
1	4	4	4	40	10	10	10	4	<4
2	0.6	2	20	6	2	2	6	<1	<1
1	3	10	3	30	10	3	10	3	<3
5	15	<5	5	5	5	5	5	5	<5
170	20	5	500	50	20	20	20	20	20
6	6	<6	60	6	20	<6	6	60	60
2	2	<2	2	5	2	<2	<2	2	2

TABLE IV (continued)

(b) Amazon region

Element	Crust* ¹	Soil* ²	FA1	FA4	FA14	FA5	FA6
B	9	10	10	2	2	250	5
F	544	100	150	150	15	700	700
S	340	1000	400	120	10	400	200
Cl	126	1500	15	150	5	50	15
Sc	25		10	10	10	30	30
V	136	100	400	400	40	400	400
Cr	122	120	20	50	20	20	20
Co	29	10	1	0.4	0.4	20	5
Ni	99	100	1	1	0.5	20	5
Cu	68	12	60	2	2	20	20
Zn	76	80	120	40	40	150	60
Ga	19	14	20	5	5	30	30
Ge	1.5		0.5	0.1	0.05	2	0.5
As	1.8	10	0.2	0.02	0.05	0.02	0.02
Se	0.05	1	0.3	0.5	0.3	0.5	0.5
Br	2.5		0.2	0.2	0.2	0.2	0.2
Rb	78	100	2	15	15	20	15
Sr	384	120	10	10	30	100	100
Y	31	50	5	40	5	60	5
Zr	162	400	200	6	200	300	200
Nb	20		40	40	40	70	50
Mo	1.2	1	1	0.3	1	1	0.1
Ag	0.08		0.1	0.04	0.04	0.5	0.04
Cd	0.16		<0.1	<0.3	<0.1	0.4	<0.1
Sn	2.1	5	10	8	10	30	15
Sb	0.2		0.7	2	0.2	2	2
I	0.46	4	3	<1	1	3	30
Cs	2.6		1	1	1	50	3
Ba	390	800	20	7	70	200	200
La	34	50	10	30	30	30	30
Ce	66		15	50	50	200	50
Pr	9.1		2	0.7	0.7	7	7
Nd	40		9	9	9	95	95
Sm	7		2	7	<2	10	6
Eu	2		2	<1	<1	6	0.7
Gd	6		7	7	2	20	7
Tb	1		<1	1	<1	10	1
Dy			6	6	2	60	6
Ho	1		<1	1	<1	1	0.1
Er	3.5		4	10	<3	120	10
Tm	0.5		0.6	0.6	0.2	30	2
Yb	3.1		<3	3	<1	30	10
Hf	2.8		5	<5	5	50	15
Pb	13	50	20	20	0.5	5	50
Th	8		6	6	6	20	20
U	2.3		2	2	2	20	2

*¹ Fairbridge (1972); *² Mitchell (see Bear, 1964).

FA7	FA8	FA9	FA10	FA11	FA12	FA13
15	5	20	2	2	2	5
100	1500	1500	150	150	450	1500
130	400	400	400	400	400	1200
10	50	50	15	50	50	1500
30	30	30	350	10	10	30
10	10	400	400	150	400	400
20	20	20	500	20	20	20
5	0.5	15	1	1	1	10
5	0.5	2	5	0.5	0.5	15
1	0.5	20	5	20	20	60
120	120	120	40	40	40	120
60	60	20	5	5	5	20
0.5	0.05	0.2	0.5	0.2	0.5	5
0.02	<0.01	0.02	0.2	2	0.5	1
<0.01	0.01	0.3	0.3	0.5	0.5	0.5
2	<0.2	<0.2	0.2	0.2	0.5	2
45	15	2	5	15	5	150
30	3	10	30	10	3	350
10	1	5	40	5	10	40
600	20	50	200	150	60	300
130	5	5	15	40	5	150
0.1	0.03	0.1	1	0.5	0.5	0.5
0.04	0.01	0.01	0.1	0.04	0.1	0.04
<0.1	<0.1	<0.1	0.1	<0.1	<0.1	<0.1
8	3	10	30	5	10	3
2	0.7	0.7	2	0.3	2	0.7
3	1	3	<1	1	3	10
3	3	1	1	1	3	3
70	20	700	70	70	20	700
3	1	3	30	30	10	80
50	20	50	50	50	20	550
0.7	0.2	2	2	2	0.7	25
10	3	30	30	30	10	10
2	2	2	6	2	2	2
0.1	0.1	1	0.7	0.7	0.7	2
7	2	7	2	7	2	70
0.3	0.3	1	0.3	0.3	<1	3
6	0.6	6	6	6	2	6
0.1	0.04	<1	0.4	0.4	<1	0.4
<4	<4	<4	4	<4	<4	4
2	<1	<1	<1	<1	2	<1
10	1	3	1	1	<3	1
15	5	5	5	5	<5	5
20	5	5	5	5	20	90
6	2	0.5	20	20	20	60
2	0.5	0.5	5	2	5	5

TABLE IV (continued)

(c) *Goiás region*

Element	Crust* ¹	Soil* ²	75-1A	75-1B	75-2A	75-2B	75-3A	75-3B	75-4A
B	9	10	170	50	500	> 500	500	50	170
F	544	100	> 250	80	250	> 250	250	80	> 250
S	340	1000	80	25	25	8	25	8	250
Cl	126	1500	170	170	170	> 500	500	170	> 500
Sc	25		10	30	10	30	10	10	30
V	136	100	80	80	80	25	25	25	10
Cr	122	120	2	5	2	5	2	2	5
Co	29	10	<1	1	0.3	1	0.3	0.3	1
Ni	99	100	15	15	15	50	15	15	15
Cu	68	12	5	5	5	5	5	20	20
Zn	76	80	1	1	0.5	1	1	0.5	1
Ga	19	14	6	6	6	20	6	6	6
Ge	1.5		1	2	2	2	2	1	2
As	1.8	10	7	7	2	7	1	0.2	1
Se	0.05	1	0.03	0.03	0.03	0.03	0.01	< 0.01	0.03
Br	2.5		0.5	2	0.5	0.5	0.5	0.2	0.5
Pb	78	100	1	1	5	15	1	1	45
Sr	384	120	10	10	3	10	10	3	10
Y	31	50	12	12	35	35	12	12	4
Zr	162	400	200	600	600	600	200	200	200
Nb	20		13	40	13	13	13	4	4
Mo	1.2	1	1	1	3	1	1	1	1
Ag	0.08		0.04	0.04	0.1	0.04	0.04	0.04	0.04
Cd	0.16		<0.1	0.1	<0.1	0.1	<0.1	<0.1	0.1
Sn	2.1	5	3	9	25	3	3	3	9
Sb	0.2		2	7	1	7	2	2	7
I	0.46	4	10	10	3	10	1	1	3
Cs	2.6		0.3	1	10	10	1	0.3	10
Ba	390	800	7	7	70	70	2	2	200
La	34	50	8	8	8	3	3	3	8
Ce	66		16	50	16	16	2	16	50
Pr	9.1		0.7	2	0.7	0.7	0.7	0.7	2
Nd	40		3	3	3	1	3	1	3
Sm	7		7	2	2	2	2	<2	2
Eu	2		0.2	0.2	0.2	0.2	0.2	<0.2	0.2
Gd	6		2	2	2	0.7	0.7	0.7	0.7
Tb	1		0.3	0.3	0.3	0.1	0.1	0.1	0.1
Dy			2	2	2	2	2	0.6	2
Ho	1		0.3	0.3	0.3	0.3	0.1	0.1	0.1
Er	3.5		4	4	4	1	1	1	1
Tm	0.5		0.6	0.6	0.6	0.2	0.6	0.2	0.6
Yb	3.1		3	3	3	1	1	1	1
Hf	2.8		5	15	15	15	5	5	5
Pb	13	50	20	20	20	20	5	20	50
Th	8		20	20	20	20	20	6	6
U	2.3		2	5	2	5	2	2	1

*¹ Fairbridge (1972); *² Mitchell (see Bear, 1964).

75-4B	75-5A	75-5B	75-6A	75-6B	75-8A	75-8B	75-9A	75-9B
50	50	170	5	50	50	50	50	170
250	80	80	> 250	> 250	> 250	80	80	> 250
25	80	8	25	25	25	8	25	25
> 500	500	50	50	50	500	170	> 500	50
10	10	10	10	10	10	30	10	100
25	25	25	10	10	80	80	25	10
2	2	0.5	2	5	2	5	5	0.5
1	0.3	0.1	0.3	1	0.3	1	0.3	1
15	15	5	15	15	15	15	15	15
5	2	2	5	5	20	5	5	5
0.5	0.3	0.1	0.1	1	1	1	1	1
6	6	6	3	6	20	6	6	20
1	2	1	1	1	2	2	2	1
1	2	2	2	2	7	7	7	7
0.01	0.1	0.1	0.03	0.1	0.03	0.03	0.03	0.01
0.5	2	0.5	0.5	0.5	0.5	2	0.5	0.5
45	5	1	1	5	1	1	1	1
10	10	1	3	10	10	10	10	30
4	12	4	4	4	12	12	12	12
60	200	200	60	200	600	600	600	200
4	13	13	4	4	13	40	13	13
0.3	3	1	1	3	1	1	1	1
<0.04	0.1	0.04	<0.01	0.04	0.04	0.04	0.04	0.04
<0.1	0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
3	9	3	3	9	3	3	3	1
2	7	2	2	7	2	7	7	2
3	10	3	1	3	10	10	10	10
3	3	3	1	3	1	1	1	3
70	7	7	20	70	7	7	7	2
8	3	1	80	8	3	8	8	1
50	16	5	16	50	16	16	16	16
2	0.7	0.2	2	0.7	0.7	0.7	0.7	0.7
10	3	1	1	3	3	3	3	3
2	2	<2	2	2	2	7	2	2
0.2	0.2	<0.2	0.2	0.2	0.2	0.2	0.2	0.2
0.7	0.7	<0.7	0.7	2	0.7	0.7	2	0.7
0.1	0.1	<0.1	0.1	0.1	0.1	0.1	0.3	0.1
2	2	<0.5	0.5	2	2	2	2	2
0.1	3	<0.1	0.1	0.1	0.3	0.3	0.3	0.1
<1	1	<1	1	1	4	4	4	1
0.2	0.6	0.2	0.2	0.6	0.6	0.6	0.6	0.2
1	1	<1	1	1	1	3	3	1
<5	15	5	5	5	15	15	15	5
20	20	5	20	50	5	5	20	5
2	20	6	2	6	20	20	20	20
1	2	2	<1	2	2	5	2	2

Some general features of abundances are apparent:

(1) The number of elements with enriched concentrations is correlated with the degree of weathering (Fig. 4). At the Bahia sites, where the terrain appears less weathered, there are 41 elements having enriched (e or xe) concentrations with respect to crustal abundance. By comparison, in the kaolinitic and gibbsitic environments there are 22 elements and 11 elements respectively in these categories.

(2) In the gibbsitic environment (Table V), the enriched elements (B, Cl, Sn, I, Sc, Zr, Hf, As, Sb, Cs, Pb) include elements established as bio-important (B, Cl, Sn, I). Also included are elements (Sc, Zr, Hf) considered refractory in terms of oxides solubility and melting points. The weathering chemistry of As and Sb is not established, but they are known to be concentrated in soils (Wedepohl, 1969). The enrichment of Cs and Pb is surprising, although they, too, have been reported to be concentrated in soils (Wedepohl, 1969).

TABLE V

Average enrichment status of elements with respect to crustal abundance

Element	Bahia	Amazon	Goias	Element	Bahia	Amazon	Goias
B	s	d	e	Y	s	s	s
F	s	d	s	Zr	e	s	s
Na	xd	xxd	xxd	Nb	s	s	s
Mg	xd	xxd	xxd	Mo	s	s	s
Al	s	s	s	Ag	s	s	s
Si	s	s	s	Cd	s	s	s
P	s	d	d	Sn	e	e	s
S	s	s	xd	Sb	e	e	e
Cl	e	d	s	I	e	e	e
K	d	xd	xd	Cs	s	s	s
Cu	xd	xxd	xxd	Ba	s	d	xd
Sc	e	s	s	La	s	d	d
Ti	s	s	s	Ce	s	s	d
V	d	d	d	Pr	s	d	d
Cr	s	d	xd	Nd	s	d	xd
Mn	s	d	d	Sm	s	d	d
Fe	s	s	s	Eu	s	d	d
Co	s	d	xd	Gd	s	s	d
Ni	d	xd	d	Tb	s	d	d
Cu	s	d	xd	Ho	s	d	d
Zu	s	s	xd	Er	s	s	d
Ca	s	s	d	Tm	s	s	s
Ge	s	s	s	Yb	s	s	s
As	s	d	s	Hf	s	s	s
Se	s	e	s	Pb	e	s	s
Br	s	d	s	Th	s	s	s
Rb	d	d	xd	U	s	s	s
Sr	xd	xd	xd				

A further contribution to soils may come from aerosol fallout. As reported in Valković (1975) elements such as Cu, Zn, Sn, Pb are highly enriched in airborne particulates. Aerosol and rain make non-trivial contributions to soils. Thus some elements, Cl, Na, Mg, K, Ca may be added at levels near $1 \text{ kg ha}^{-1} \text{ yr}^{-1}$. In fact, such fallout may be vital to the growth of forests on highly leached soils.

(3) In the kaolinitic material (Table V), the enriched elements include more refractory elements (Sc, Zr, Nb, Gd, Tb, Tm, Yb, Hf, Th) and more bio-important elements (B, S, Cl, Cr, Se, Sn, I). Ag, Cs, Pb and U may be exhibiting biological affinity. Sb is enriched again and Ga could be substituting for Al.

(4) In the more complex weathering environment of Bahia (Table V), even more bio-important elements (B, F, Cl, Cr, Co, Cu, Zn, Se, Mo, Sn, I) are concentrated. The refractory metals enriched include Sc, Y, Zr, Nb, La, Ce, Pr, Nd, Sm, Eu, Gd, Tb, Ho, Er, Tm, Yb, Hf, and Th. Other metals with enriched concentrations are Ga, Sr, Ag, Cs, Ba, and Pb. Non-metallic enrichments include the semi-metals Ge, As and Sb.

(5) No rare-earth elements are enriched in the highly weathered gibbsitic environment. Some heavy rare-earth elements (Gd, Tb, Tm, Yb) are enriched in the Amazon samples, and in the material from Bahia enrichment occurs for both light and heavy members.

(6) Enrichment for the first-row transition metals (Sc, Ti, Cr, Fe, Co, Cu, Zn) is common in the less weathered region with smectite clays. In the kaolinitic regime only Sc, Ti, Cr and Fe are concentrated while in the gibbsitic environment only Sc is enriched.

(7) Very strong depletions (xxd) occur mainly for alkali metals or alkaline earths, and some first-row transition metals.

(8) In the Amazon and Bahia profiles there are no progressive changes with depth in mineralogy or in concentrations of the major and trace elements. In other work on the weathering of granulitic rocks (Sighinolfi et al., 1973) in the Bahia region, no pattern of gains and losses were observed, and, in general, correlations between elements in the rocks were not maintained in the residual soils.

(9) In the surface soils in the Amazon and Bahia regions where organic debris is present, there are anomalously high concentrations of some elements. It seems possible that such elements are exhibiting some form of biological affinity. Included here are: Cs, Gd, Dy, Er, Tm, Yb, Hf, Th and U in FA5; Sc in FA10 and in FB75—8.

(10) For the surface soils in the Bahia and Amazon regions, the depletion of trace elements is more pronounced in the cultivated soils (SB-1, SB-3, SB-5, FA14). SB-2 is an exception in accordance with its mineralogy and macrochemistry. The depleted elements are most often those known as micronutrients (B, Cl, V, Cr, Mn, Co, Cu, Zn, Se, Mo, Sn, I) considered essential for biochemical processes (Frieden, 1972).

TIME CONSTANTS OF FORMATION OF LATERITES

How long does it take to form a deep, 100 m, profile of the type described here for the Amazon? It appears to us that it is possible to place some limits from the geochemistry. Let us first consider that a column of rock is leached in situ and replaced volume for volume by kaolinite, etc. We assume that all Al is retained.

Almost all groundwater, river water, etc., has K at about the 2 ppm level. Assuming that our profile had about 3% K in its original state, then for 1 m of rain per year, it would require $5 \cdot 10^6$ years to remove the K. Obviously, this figure is too low. As K is leached, the level of K in solutions will fall. This, in fact, is shown by Amazon water which tends to have low K (1 ppm). Hence a figure of 10^7 years or more is probably more appropriate. A similar number can be derived by consideration of leaching of SiO_2 . Again, the equal volume model is conservative in that many enrichments require that the original column is larger than the final laterite column.

We conclude, that times of tens of millions of years are required to form the very thick laterite profiles observed. This also requires a very stable cratonic region of constantly low topography, i.e. a very stable geologic environment free from major erosional events such as ice ages. In fact, some of the laterites of Brazil may well have been in the process of formation since the Atlantic Ocean opened.

CONCLUSIONS

(1) Intensive chemical weathering of continental crust leads to highly leached soils with rather simple chemistry and mineralogy. The main components (SiO_2 — Al_2O_3 — Fe_2O_3 — H_2O) are bound mineralogically as quartz, gibbsite, kaolinite, goethite and hematite. Many millions of years must be involved in the formation of thick lateritic profiles.

(2) Trace-element concentrations in highly leached soils are generally similar to or depleted relative to crustal abundances. Generally, enrichments are common only for bio-important elements and the least soluble refractory oxides.

(3) The indication is that for many trace elements, concentration during weathering is transient, and may be controlled by the dominant clay minerals. The montmorillonite and illite group minerals (Bahia region) retain higher concentrations of trace elements than kaolinite (Amazon region) and gibbsite (Goias region).

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