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Clay minerals in a soil chronosequence derived from basalt on Hainan Island, China and its implication for pedogenesis

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ABSTRACT

A soil chronosequence consisting of six profiles formed on quartz tholeiite basalt ranging in age from 10,000 years to 1. 8 Million years (My) was studied here. Soil clays were identified using XRD diffractogram decomposition methods for samples obtained from the A and C horizons of profiles. The results showed that kaolinite minerals dominated in all the clay fractions. Gibbsite was prominent in the C horizons in the soils from older rocks. Clays in the A horizon of relatively young soils showed an initial stage of illite formation, followed by smectite mixed layer minerals (illite–smectites and then vermiculite–illite) and finally by vermiculite. The initial presence of illite is interesting as there is no magmatic micaceous or phyllosilicate phase in these basalts and the formation of illite we attribute to a secondary process, probably created by alkali transport by plant materials. The change in 2:1 clay mineralogy reflects the overall change in Si/Al ratios in the soils over longer periods of weathering. In all cases gibbsite is more abundant in the C horizons than the A horizons. The difference in gibbsite content between the A and C horizons we attribute to plant transport of siliceous phytolite material to the surface. Continued high rainfall over long periods of time removed the alkali faster than the plants could bring it to the surface, which led to continuous lowering of 2:1 minerals from younger to older in the soil chronosequence. Nevertheless a 2:1, silica-rich mineral persists in the clay assemblages although in very minor amounts.

1. Introduction

It is well known and accepted that normal weathering due to water–rock interactions, is the loss of alkali and alkaline earth elements followed by silicon, which results in the production of an oxide and oxyhydroxide assemblage consisting of aluminium and iron. This elemental loss sequence is reflected in the typical clay mineral weathering sequence of illite to smectites to kaolinite to gibbsite and iron oxides (oxides and oxyhydroxides of Fe). The characterisation of this sequence, which is driven by climate, is shown by the presence of illite in cold climate soils, smectites in temperate climate soils, kaolinite in semi-tropical climate soils and finally oxides under conditions of intense tropical weathering. Generally, weathering intensity is considered to be controlled by climate (Pedro, 1966; White and Blum, 1995; Chadwick et al., 2003).

It is known that in certain cases, plants appear to concentrate specific elements which form clay minerals in soils. Some temperate and tropical soils show a concentration of silica at the surface forming kaolinite, which is attributed to silica enrichment by plants (Lucas et al., 1993; Alexandre et al., 1997; Meunier et al., 1999). Control of the silica content in soil of forest soils has been shown by Farmer et al. (2005) and Gerard et al. (2008). Several studies have concluded that silica and potassium can be concentrated in the upper most parts of soil profiles, apparently due to plant activity (Jobbagy and Jackson, 2001; Barre et al., 2007). One clear example of the chemical variation between surface and deeper horizons can be seen in the data presented by Meijer and Buurman (2003), which show that the silica and potassium contents increase towards the A horizon, an effect accentuated by plant activity at lower altitudes in a sequence of tropical forest soils developed on andesitic materials in Costa Rica. It is clear that plant activity counters normal weathering in the A horizon of soils. However, there is a general, inevitable, and overall trend of weathering due to water–rock interactions where alkali and alkaline earth elements are being lost as well as silicon, although this trend is mitigated, to a certain extent, by plant action.

It is almost impossible to investigate soil development by following a single soil profile through time because these processes are too slow to test, but by substituting space for time, one can compare different age profiles developed on chemically similar parent material and interpret the results as a developing sequence. Based on

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careful sampling design and previous studies, we selected a soil sequence developed on quartz tholeiite basalts on Hainan Island (southern China) as a time series ranging in age from 10,000 y to 1.8 My (Ho et al., 2000; Huang et al., 2004; Zhang et al., 2007). The soils developed on the basalts appear to be undisturbed, i.e. with untruncated profiles and varying vegetation regimes. Since basalts have no phyllosilicate precursor minerals and contain only small amounts of glass, we can deduce that the clay minerals present represent new minerals formed as a result of the weathering of crystalline phases in the basalts and eventual development in the soils. Therefore, the main aims of this research were: a) to verify the normal trend of weathering and to observe the clay minerals present in the soils formed on basalts of similar composition as a function of the integrated time of weathering of the materials under field conditions; b) to compare clay mineralogy assemblages in the A and C horizons of soil profiles as a function of time and to test the hypothesis of plant translocation of elements in the soil profiles.; c) to link the stage of soil development to aspects of soil chemistry and soil-forming factors.

One should keep in mind that the climate, and hence vegetation and rainfall, have not been constant over the last million years. Numerous periods of glaciation, and hence climate change, have inevitably affected the soil formation processes even towards the equator at the latitude of Hainan island. The scale of time is not constant in its effect on weathering processes. However one can make a general comparison over the time period of the general influence of weathering on the clay mineralogy and the chemistry of the soils.

2. Materials and methods

2.1. Sites and sampling

Hainan Island is the largest tropical island of China. It is located in the South China Sea, on the northern fringe of the tropical zone. The study was conducted in the northeast area of Hainan Island which has a present mean annual rainfall of 1,400 to 1,800 mm and a mean temperature of 23–24 °C. This suggests a tropical monsoon climate with contrasting seasons. The dominant parent rocks of soils on the island are basalt, granite and granodiorite. Six profiles derived from basalt were classified in this study as Primosols to Ferralsols (Chinese Soil Taxonomy (CST), 2001; Zhang et al., 2007), or equivalent to Entisols to Oxisols (Soil Survey Staff, 2003). Soils were sampled by genetic horizon (Tables 1 and 2). Chemical and mineralogical data for the basalts studied are outlined in Ho et al. (2000), where the basalt bedrock was dated using K–Ar methods. Differences in basalt age may provide a sequence in the intensity of chemical weathering. The younger rocks retain primary minerals and indicate rapid weathering rates, while soils in the oldest rocks are already deeply weathered and composed of secondary minerals which weather slowly. The soil samples investigated here were taken from the A and C horizons of the profiles in order to observe and compare the effects of weathering at the surface where weathering effects should be strongest.

Table 1
Soil types found on Hainan Island basalts

Profile	Sampling sites	Soil type (CST)[a]	Soil type (WRB)[b]	Basalt age (10^4 y)[a]
HE09	Shizilu, Qiongshan	Primosols	Luvisols	1
HW03	Yangpu, Danzhou	Cambosols	Cambisols	9.0±2.0
HE05	Shizipo, Dingan	Cambosols	Cambisols	14.6±0.9
HW04	Deyiling, Danzhou	Ferrosols	Lixisols	64
HE10	Yunlong, Qiongshan	Ferrosols	Lixisols	133±18
HW02	Xinying, Danzhou	Ferralosols	Ferralsols	181±8

[a] From Zhang et al. (2007).
[b] Based on FAO (2006).

Table 2
Elevation and vegetation on soils studied

Profile	Elevation (m)	Present vegetation
HE09	50	Sparce grass and shrub land
HW03	20	Secondary shrubs, Eupatorium odortum cactus, willow
HE05	90	Cassava
HW04	50	*Acacia confuse*, shrubs
HE10	70	*Acacia confuse*, *Eucalyptus*
HW02	120	Secondary shrubs, willow

2.2. Soil chemistry

The soil samples were air-dried, crushed using a wooden pestle and mortar, and then passed through a 2 mm nylon sieve. Soil pH was determined by a 1:2.5 soil: solution ratio using distilled water (Nation Soil Survey Center, 1996). Routine chemical analyses for organic carbon (OC), cation exchange capacity (CEC) and total analysis (such as Si and K) were based on standard techniques (ISSCAS, 1978). Some of the chemical tests carried out on this soil chronosequence have been measured by Huang and Gong (2001) and Zhang et al. (2007).

2.3. Soil mineral identification and grain sizes

Particle-size distribution in soils was determined by the pipette method (ISSCAS, 1978; Nation Soil Survey Center, 1996). The clay fraction (<2 μm) was obtained from the soil after buffering with Na-acetate (pH=5) and oxidizing the organic matter with dilute H_2O_2 and by dispersion with Calgon and sedimentation in water.

The clay fraction was flocculated (several drops of $SrCl_2$ solution) and deposited on a glass slide. No chemical treatment was performed on the material before the X-ray diffraction (XRD) diagrams were obtained in order to observe the clays as they function in the soils, i.e. without altering their expandability characteristics (e.g. Velde, 2001). Glycol treatment was carried out in all samples.

Table 3
Descriptions and some chemical characteristics of soil profiles

Profile	Depth (cm)	Horizon	Color (dry)	pH (H_2O)	CEC (cmol (+)/kg)	OC (g/kg)	SiO_2 (g/kg)	Al_2O_3 (g/kg)	K_2O (g/kg)
HE09	0–15	Ap	10YR 4/4	6.38	20.75	13.52	389.88	213	2.77
	15–30	AC	10YR 3/2	6.57	20.81	6.86	352.62	238.98	2.45
	30–50	C1	10YR 3/1	7.13	21.06	4.9	354.54	242.84	1.48
	50–80	C2	10YR 8/1	6.87	22.68	3.38	393.63	208.41	1.88
HW03	0–12	A	7.5YR4/6	6.17	23.43	25.37	347.82	201.8	3.01
	12–44	AC	7.5YR4/6	6.13	22.1	11.94	347.94	231.09	3.19
HE05	0–15	A	10YR3/3	5.57	12.13	15	417.94	196.94	4.1
	15–35	AB	10YR3/3	5.49	9.48	9.57	416.54	201.53	3.54
	35–50	B	10YR3/3	6.06	9.67	8.18	404.95	200.61	2.67
	50–75	C	10YR3/3	6.3	10.94	7.25	417.47	248.35	3.37
HW04	0–6	A	5YR 3/4	4.75	19.45	30.3	407.1	191.03	3.1
	6–22	AB	5YR 3/6	4.72	15.14	11.3	400.59	210.11	3.73
	22–37	B	5YR 3/6	5.25	15.92	9.22	376.61	220.32	4.1
	37–65	BC	5YR 3/5	5.1	14.39	8.29	386.13	220.32	3.72
	65–100	C1		5.61	16.56	5.77	334	247.71	3.39
HE10	0–25	A	5YR 5/8	4.49	5.45	9.22	263.27	290.79	2.92
	25–50	AB	5YR 5/6	5.27	3.84	4.34	257.72	310.63	2.96
	50–70	B1	5YR 5/6	5.23	4.03	5.68	268.57	299.11	2.66
	70–90	B2	5YR 5/6	5.11	4.15	5.8	271.35	333.28	1.72
	90–120	B3	5YR 5/6	4.79	3.23	10.5	276.3	294.57	2.26
	>120	BC	5YR 5/7	4.77	2.81	8.82	273.98	338.79	2.05
HW02	0–25	A	2.5YR3/6	4.17	6.08	20	255.59	298.92	2.25
	25–52	AB	2.5YR3/6	4.85	2.94	8.76	258.82	312.71	2.35
	52–88	B1	2.5YR4/6	4.82	2.82	5.13	257.86	313.85	1.74
	88–128	B2	2.5YR4/6	4.64	3.66	3.43	252.48	314.98	1.47
	128–150	B3	2.5YR4/6	4.73	4.15	3.77	251.32	314.41	2.09