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Mobilization and redistribution of elements in soils developed from extreme weathering basalt on Hainan Island

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Abstract Major, trace and organic elements of a laterite profile developed on Neogene basalt on Hainan Island, South China were reported to investigate elements mobilization and redistribution in tropical regions. The results indicate that strong acid environment and organic matter (OM) can remarkably improve the transfer of insoluble elements. Among all the elements, Th is the least mobile. As for the general conservative elements during incipient chemical weathering, such as Ti, Zr, Hf and Nb, the removals are up to 30%–40% in the upper profile. And for Fe, Al, Cu and Ni, that tend to be combined with secondary minerals and to be retained in temperate zone, they are removed from the upper profile, transferred downwards, and then precipitated in the lower profile. In addition, atmospheric inputs, including sea salt aerosols and dust, have a profound effect on the budgets of elements that are susceptible to leaching losses (e.g. K, Na and Sr). Excluding the possibilities of groundwater and erosion, the remarkable increase of K, Na and Sr concentrations in the upper profile, together with dramatically upward increasing trends of the percentage changes of Sr/Th, K/Th and Na/Th ratios, show that atmospheric inputs, especially sea salt aerosols, contribute much extraneous seawater derived elements, such as K, Na and Sr to the soils. The overall elemental behaviors in this profile suggest that organic matter and atmospheric inputs play a very important role in the mobilization and redistribution of elements during extreme weathering in tropical regions.

Key words basalt; extreme weathering; Hainan Island; atmospheric inputs

1 Introduction

Chemical weathering is one of the most important processes that change the chemical composition of the Earth's surface. Primary minerals can be decomposed by chemical weathering of rocks in the continent and many elements can be activated. As a result, the redistribution of elements in weathering products is much different from that in parent rocks (Nesbitt, 1979; Nesbitt et al., 1980; Nesbitt and Markovics, 1997). Weathering products are easily separated out of weathering profiles and deposited in lakes and oceans as the main lithogeneous component in sediments (Windom, 1976). Therefore, the mobilization and redistribution of elements during chemical weathering may influence the genesis of soils and chemical composition of sediments. Chemical compositions of sediments and soils have been used effectively to evaluate weathering and soil formation conditions, to trace the provenance of sediments and soils (Nesbitt et al., 1996) and to reconstruct paleoclimate records (Zabel et al., 2001; Wei et al., 2004). Thus, quite a number of studies have been carried out in the past several decades to investigate chemical weathering (Quantin et al., 1991; Price et al., 1991; Nesbitt and Wilson, 1992; Cotten et al., 1995; Nesbitt and Markovics, 1997; Hill et al., 2000; Patino et al., 2003; Little and Aeolus Lee, 2006).

Most of the studies mentioned above, however, were carried out in temperate zones with weathering intensities from incipient to advanced degree. The behavior of elements during extreme weathering has been far less studied, and the mechanisms involved in elements redistribution or mobility during chemical weathering processes are not fully understood. Previous studies show elements that are conserved in temperate zone, such as Ti and Zr, are mobile during extreme chemical weathering in tropical regions (Nahon and Merino, 1996; Cornu et al., 1999). On the other hand, atmospheric inputs, including sea salt aerosols and dust, have a profound effect on the budgets of elements that are susceptible to leaching losses during extreme weathering processes in tropical regions (Kurtz et al., 2001). Chadwick (1999) also argued that inputs of elements from the atmosphere can sustain the productivity rainforests on highly weathered soils in tropical Hawaii. Atmospheric inputs have become the dominant source of soil nutrients, such as K, P and Sr, in the near-surface horizons (0–50 cm depth) of the oldest, most intensely weathered soils (Kennedy, 1998). Thus, the mobilization and redistribution of elements during chemical weathering in tropical regions are different from those of temperate zones (Young and Nesbitt, 1998; Hill et al., 2000; Kurtz et al., 2000; Dequincey et al., 2002).

Extreme weathering is the highest stage of weathering process. Probing into element behavior during this particular period is pivotal to understanding element mobilization and redistribution during chemical weathering. In addition, laterites, the products of extreme weathering, account for over 85% of the present world soil cover (Nahon, 2003). They are readily eroded from profiles and transported into oceans, and their chemical compositions may be imprinted into sediments. Therefore, comprehensive understanding of the behavior of elements during extreme weathering in the tropical laterite profile may aid in our understanding of the mechanisms of weathering and help to better explain the chemical record in sediments and soils.

Hainan Island, located in the tropical zone and most of the weathering profiles in this region have undergone extensive weathering (Huang et al., 2004; Zhu et al., 2006), which provides an excellent opportunity to study the behavior of elements during extreme weathering. In addition, because basalts are very sensitive to chemical weathering (Berner and Berner, 1997), the development of soils on relatively pure basalt regolith facilitates us to focus on the behavior of elements during extreme weathering. Therefore, we report some major and trace elements of a laterite profile developed on basalt in Hainan Island, South China. In this paper, we compare the composition of weathering products with fresh parent rocks, and use mass balance modeling to evaluate mobility and losses of elements. The goal of this study is to investigate elements mobilization and redistribution during the processes of advanced to extreme weathering in tropical climates.

2 Materials and methods

2.1 Sampling site and pedon description

Hainan Island is the largest tropical island of China. It is located in the South China Sea, on the north fringe of the tropical zone. The study was conducted in the northeast of Hainan Island which has a mean temperature of 23−24℃ and a present mean annual precipitation of 1400 to 1826 mm. This suggests a tropical monsoon climate with contrasting seasons. Numerous lateritic weathering profiles have developed on the basalts, which erupted during the Neogene and Quaternary in the northern Hainan Island (Huang et al., 1993). The basaltic weathering profile under study is located in Chengmai County, about 25 km south of Haikou, capital city of Hainan Province (Fig.1). The age of the basalts in this region is ～3.76 Ma dated by K-Ar chronology (Ge et al., 1989).

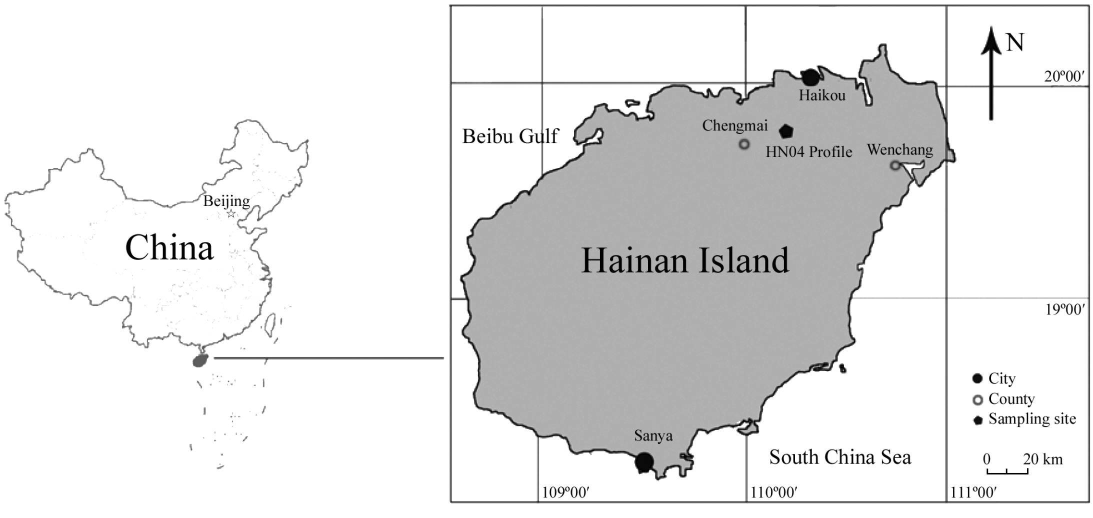

Fig. 1. Location of the sampling site.

The profile locates on a small hill (19°53′59″ N, 110°07′25″ E), which has been recently cut by a stone quarry. The slope of the hillside is gentle, and the sampling profile was selected in the middle of the hillside, which is newly cut and has a flat top. The top 30 cm is loose soil, covered with flouring plants. The soil between 30 and 150 cm is fine laterite in a homogeneous red color (Table 1). The soil color turns yellowish from 150 to 180 cm. Below 180 cm, the soil color becomes pistachio with un-weathered core stones, and black shell-shaped matter fills the area between the core stones. Interruption is not observed in the inter gradation from basalts to laterites, and the laterites are *in-situ* weathering products developed from the basalts.

Soils were sampled by genetic horizon (Table 1). The parent rock is fresh tholeiitic basalt, which was collected beneath the sampling profile. Soil samples investigated here were taken from 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. In addition, soil profile is under secondary shrub or forest vegetation, which has udic soil moisture regimes and hyperthermic soil temperature regimes. The soils are classified as Ferralsol according to the Chinese Soil Taxonomy [Chinese Soil Taxonomy (CST), 2001; Zhang et al., 2007], or equivalent to Oxisol according to USDA Soil Taxonomy (Soil Survey Staff, 2003).

2.2 Laboratory analyses and calculations

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 (Soil Survey Staff, 1996). Routine chemical analyses for organic matter (OM) were based on standard techniques (ISSCAS, 1978). Samples were dissolved with acid solution to measure the concentrations of trace elements at the State Key Laboratory of Mineral Deposit Research, Nanjing University, on a JY 38S (JION YVON, France) single channel scanning plasma spectrometer. The detection limit of the instrument: 0.1–0.01 μg/g, RSD≤2%. The major elements were determined by routine methods after they were decomposed with alkaline fusion (Soil Survey Staff, 1996).

One approach to determine chemical losses during weathering of primary minerals is to determine the ratio of chemical concentration in the weathered mineral to the corresponding concentration in the parent mineral. The mass ratio of chemical components in weathered and parent minerals, however, is also a function of dilution effects caused by losses and gains of other components. One way to deal with this problem is to define the ratio of different components in terms of a conservative (immobile) element whose absolute value is considered to remain constant during weathering of the protolith. The percent change in the ratio relative to the ratio in the parent sample is then defined according to Nesbitt and Markovics (1997) as:

$$\text{Change of ratios}=100\times[(R_\text{i}-R_\text{p})/R_\text{p}]\ (\%)$$

where R_i and R_p represent the ratio of element to a conservative element in weathered samples and fresh basalt, respectively.

3 Results

Major and trace elements concentrations of the laterite profile developed on Neogene basalt in Hainan Island, South China are listed in Table 2. SiO_2, Al_2O_3 and Fe_2O_3 are dominant chemical compositions for all soil samples, and Al_2O_3 (15.89%–24.66%), Fe_2O_3 (13.00%–20.34%) and TiO_2 (2.92%–3.81%) are markedly enriched in the weathering products, which are about 1.5- to 2-fold higher than in the fresh basalt. SiO_2 concentrations in weathering products range from 37.03% to 56.21%, compared with 50.42% in the fresh basalts. On the contrary, concentrations of MgO (0.23%–0.34%), CaO (<0.24%), and Na_2O and K_2O (<0.1%) are dramatically lower than these in the fresh basalt. It is worth noting that concentrations of CaO, Na_2O, MgO and K_2O in the weathering products are extremely low compared to that in the fresh basalt (Table 2). They are even significantly lower than those in the advanced weathering zone reported by Nesbitt and Wilson (1992). Thus, nearly all the alkalis and alkaline earth elements and Al_2O_3, Fe_2O_3 and TiO_2 are very high, with maximum values up to 24.66%, 20.34% and 3.81%, respectively. These results suggest that the profile has undergone an extreme weathering.

Nesbitt and Wilson (1992) divided basaltic weathering profiles into four qualitative categories: incipient, intermediate, advanced and extreme. Several indices, such as chemical index of alteration (CIA), weathering index (ba) and intensity of chemical weathering (CIW) have been proposed to evaluate the intensity of chemical weathering (Parker, 1970; Nesbitt, 1979; Harnois, 1988). CIA value of fresh basalt is 48.28%, while those of soil samples range from 93.98% to 97.78%. Similarly, CIW value of fresh basalt is 50.17%, while those of soil samples vary from 97.76% to 99.36%. Ba value of fresh basalt is 1.07, but the values of soil samples range from 0.2 to 0.6 (Table 3). As a result, extremely low concentrations of CaO, Na_2O, MgO, K_2O and low Ba values, together with high concentrations of Al_2O_3, Fe_2O_3, TiO_2 and high values of CIA and CIW, strongly indicate that the chemical weathering intensity in this profile could be categorized as extreme (Nesbitt and Wilson, 1992).

In addition, trace elements in the weathering products, except for Rb, Sr, Ba and Y, are higher than those in the fresh basalt (Table 2). With the increase of weathering intensity, most trace elements show higher concentrations in the lower profile than in the upper profile. TOC concentrations vary from 2.65 to 18.27 g/kg (Table 1). TOC concentrations are high in the top section, and decrease successively downwards in the profile.

Table 1 Soil properties for the soil profile in Hainan Island

Depth (cm)	Horizon	Color (dry)	pH (H_2O)	TOC (g/kg)
0–15	A	2.5YR4/6	5.37	18.27
15–30	AB	2.5YR5/6	5.76	10.38
30–55	B1	2.5YR5/4	5.69	7.77
55–80	B2	2.5YR5/4	5.68	5.55
80–100	B3	2.5YR5/4	5.90	4.46
100–120	B4	2.5YR5/4	6.45	4.68
120–150	B5	2.5YR5/4	6.26	3.82
150–180	BC	5YR5/6	5.93	3.57
>180	C	5YR4/6	5.84	2.65

4 Discussion

4.1 Influence of acid environment and organic matter on the transfer of insoluble elements

4.1.1 Conservative elements

The conservative element can be used as a reference to study the mobility of other elements, and its selection may vary in different profiles. Zr has been used in granitic weathering profiles (Nesbitt and Markovics, 1997), and Ti is generally used as the conservative element in basaltic weathering profiles (Nesbitt and Wilson, 1992; Hill et al., 2000). Hf, Nb and Th are also potential conservative elements in basaltic weathering profiles because they are generally hosted in resistant minerals (Nesbitt and Wilson, 1992; Braun et al., 1993; Hill et al., 2000; Kurtz et al., 2000). However, resistant heavy minerals, such as zircon, are not identified in the cryptocrystalline groundmass of fresh basalt or in weathering products. Thus, it is difficult to determine the least mobile elements by mineral compositions. One way to sort the conservation sequence of these elements is to compare the percentage changes of their ratios to one particular element, relative to the fresh basalt. This may provide information for the relative mobility of these elements during extreme weathering. According to Braun et al. (1993), Th is assumed to be the least mobile element, and the percentage changes of Ti, Zr, Hf and Nb to Th ratios relative to the fresh basalt are all negative in the upper 180 cm of this profile (Fig. 2). The minimum values for Ti/Th are about -42.92%, -39.09% for Zr/Th, -27.32% for Nb/Th and -32.22% for Hf/Th. This confirms the assumption that Th is the least mobile of these elements in the upper profile. Assuming Th is conservative, about 30%–40% of Ti, Zr, Hf and Nb may have been removed from the top section of the profile, indicating that these elements are quite mobile during extreme weathering.

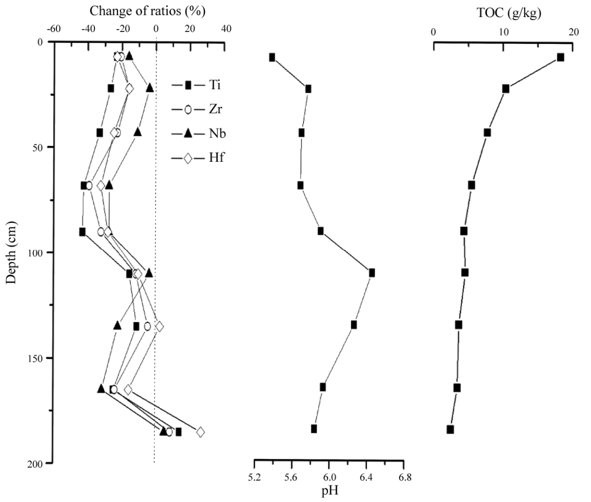

Fig. 2. In-depth variations of the percentage changes of Ti, Zr, Hf and Nb to Th ratios relative to the fresh basalt, pH values as well as TOC concentrations.

The percentage changes of these ratios are negative downwards in the profile, and become nearly constant in the section below 180 cm. From 110 to 180 cm, the averages for Ti/Th, Zr/Th, Hf/Th and Nb/Th are about -9%, -8% and -13%, respectively, suggesting a slight loss of Ti, Zr, and Nb in the lower profile. But the average for Hf/Th is about 1%, indicating a slight gain of Hf in the lower profile. However, the percentage changes of Zr/Th and Nb/Th below 180 cm are within the range of ±8% relative to the fresh basalt, suggesting that they are as conservative as Th in the lower section of the profile. Such variation patterns indicate that Ti, Zr, Hf and Nb are all mobile during extreme weathering compared to Th. They are gradually removed from the upper profile, transferred downwards, and a small part of them are retained in the lower profile. Most of these elements, however, are carried away from the profile.

It has been noted that elements that were formerly considered immobile during weathering can be leached out of weathering profiles under certain conditions (Gardner, 1980, 2000; Gardner et al., 1978, 1981; Moore, 1996). Hill et al. (2000) and Kurtz et al. (2000) have shown that elements that had been considered immobile (e.g. Y, Zr, and Ti) could be actually redistributed within the weathering profile. The basaltic weathering profile under study is located in the tropical zone and has undergone an extreme weathering, which has udic soil moisture regimes and hyperthermic soil temperature regimes. So the mobilization of these elements may be accounted for by the relatively stronger acid environment and higher organic matter in the upper profile. The acid environment favors the decomposition of the primary minerals in which these elements are hosted, and organic matter may form organic colloids that can significantly improve the transport of insoluble elements such as Ti, Zr, and Th in aqueous solution (Viers et al., 1997, 2000; Dupre et al., 1999; Oliva et al., 1999; Braun et al., 2005). The pH values are all less than 5.8, while TOC contents decrease successively downwards in the top 120 cm. Meanwhile, the percentage changes of Ti, Zr, Hf and Nb to Th ratios relative to the fresh basalt are dramatically negative (Fig. 2). Below 120 cm, with the decrease of TOC contents and high pH values, the percentage changes of Ti, Zr, Hf and Nb to Th ratios become less negative. Therefore, these elements, which seem to be transferred by organic matter, are depleted in the upper profile. In principle, Th may also be mobilized in such an acid environment and removed from the profile with organic matter. However, Th appears to be more resistant to such an environment, compared to other elements.

4.1.2 Fe, Al, Cu, Ni, Mn and Co

For evaluating mobility and losses of elements, the percentage changes of Fe/Th, Al/Th, Cu/Th, Ni/Th, Mn/Th and Co/Th ratios relative to the fresh basalt are calculated (Fig. 3). The percentage changes of Fe/Th, Al/Th, Cu/Th and Ni/Th ratios relative to the fresh basalt in the top section (0–10 cm) are all less than -40%, indicating significant removal of Fe, Al, Cu and Ni. As mentioned above, although Fe, Al, Cu and Ni tend to be combined with secondary minerals and to be retained in the soil profile in temperate zone (Chesworth et al., 1981; Nesbitt and Wilson, 1992; Nesbitt and Markovics, 1997), these elements are mobile during extreme chemical weathering in tropical regions (Melfi et al., 1996; Nahon and Merino, 1996; Cornu et al., 1999). Stronger acid environment and dissolved organic matters can significantly improve the transfer of these elements in tropical regions (Viers et al., 1997, 2000; Oliva et al., 1999; Braun et al., 2005). The acid environment is in favor of decomposition of the primary minerals, and organic matter may form organic colloids that can significantly improve the removal of Fe, Al, Cu and Ni. The percentage changes of Fe/Th, Al/Th, Cu/Th and Ni/Th ratios are significant negative, as a result, pH values are less than 5.8 and the TOC concentrations are high in the upper profile (Fig. 3). However, with the pH values becoming high and TOC contents decreasing sharply below 22 cm, the percentage changes of Fe/Th, Al/Th, Cu/Th and Ni/Th ratios become less negative, suggesting the loss of Fe, Al, Cu and Ni decrease successively downwards. The percentage changes of Fe/Th, Cu/Th and Ni/Th ratios relative to

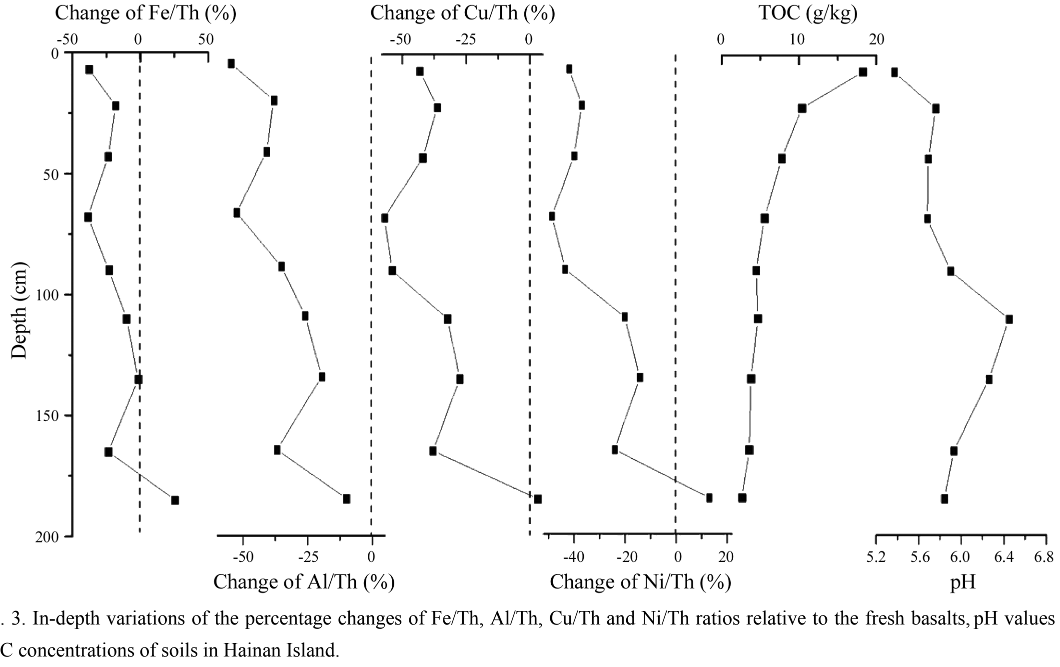

Fig. 3. In-depth variations of the percentage changes of Fe/Th, Al/Th, Cu/Th and Ni/Th ratios relative to the fresh basalts, pH values and TOC concentrations of soils in Hainan Island.

Table 2 Major element (%) and trace element (10^{-6}) concentrations of the samples from basaltic weathering profile in Hainan Island

Depth (cm)	SiO_2	Fe_2O_3	Al_2O_3	CaO	MgO	K_2O	Na_2O	P_2O_5	MnO	TiO_2	LOI	Th
7	56.21	13.00	15.89	0.10	0.34	0.65	0.08	0.22	0.15	2.92	10.44	7.65
22	51.22	14.71	18.66	0.11	0.34	0.63	0.14	0.19	0.14	3.04	10.82	6.59
43	49.66	15.77	20.49	0.04	0.33	0.60	0.11	0.22	0.13	3.15	9.51	7.58
68	46.89	16.67	21.66	0.05	0.31	0.54	0.11	0.21	0.12	3.25	10.21	9.95
90	42.50	17.25	24.44	0.03	0.26	0.41	0.06	0.19	0.10	3.35	11.41	8.24
110	43.67	17.12	23.66	0.06	0.25	0.36	0.04	0.20	0.10	3.31	11.24	6.98
135	41.70	17.96	24.66	0.04	0.24	0.32	0.07	0.19	0.10	3.51	11.21	6.70
165	42.01	17.72	24.57	0.24	0.23	0.30	0.02	0.20	0.10	3.47	11.15	8.50
185	37.03	20.34	24.49	0.18	0.25	0.19	0.02	0.26	0.12	3.81	13.32	5.94
Fresh basalt	50.42	10.42	17.49	7.65	5.80	1.26	2.09	0.40	0.16	1.96	0.74	3.82
Depth (cm)	Hf	Cr	Co	Ni	Cu	Rb	Sr	Y	Zr	Nb	Cs	Ba
7	6.3	328	72.6	151	60	36.01	20.33	8.9	888	50.3	2.07	200.0
22	5.9	271	55.1	141	58	32.65	14.10	6.7	811	49.7	2.13	162.0
43	6.1	284	48.0	154	61	40.00	18.13	8.5	856	53.0	2.52	189.8
68	7.2	328	41.3	173	59	40.89	16.99	9.6	885	56.6	3.02	200.1
90	6.3	359	30.7	158	53	28.55	13.77	7.8	817	46.9	2.44	163.6
110	6.7	371	40.3	189	66	21.73	12.00	5.6	901	52.6	2.27	173.3
135	7.3	387	41.2	195	67	17.58	11.57	5.7	935	40.9	2.09	174.0
165	7.6	380	47.2	219	73	19.13	12.40	8.4	945	45.6	2.17	196.7
185	8.0	393	82.2	228	85	12.55	12.98	7.9	942	49.0	1.44	299.7
Fresh basalt	4.1	254	49.7	130	53	24.57	382.43	67.7	557	29.9	0.48	435.5

the fresh basalt become positive at 185 cm (Fig. 3), which imply significant enrichment of these elements. Such a pattern indicates that Fe, Al, Cu and Ni are removed from the upper profile, transferred downwards, and then precipitated in the lower profile (185 cm), resulting in remarkable enrichment compared to the fresh basalt.

Different from Fe, Al, Cu and Ni, Mn is liable to be leached from primary minerals during chemical weathering of basalt (Nesbitt and Wilson, 1992). If the pH values of the soils are below 6.5, the mobilization of Mn may be increased intensely in relatively stronger acid environment. Because pH values of the soils are all less than 6.5, the percentage changes of Mn/Th ratios relative to the fresh basalts are more negative, below -40% (Figs. 2 and 4). However, Mn(II) is soluble and thus can be easily transferred by aqueous solutions. When it is oxidized into Mn(IV), Mn is insoluble in the weathering profile (Koppi et al., 1996). Because of oxidation environment in the upper profile, Mn is oxidized into Mn(IV) and precipitates as insoluble oxides or hydroxides. So the percentages of Mn/Th ratios are less negative in upper profile than in lower profile, which shows that Mn distribution is sensitive to change of redox condition in this profile. The distribution of the percentages of Co/Th is very similar to that of Mn/Th (Fig. 4). The percentages of Co/Th and Mn/Th are highly correlated, with a correlation coefficient of about 0.87 (N=8). The percentages of Co/Th are also less negative in the upper profile, but become more negative in the lower profile. This suggests that Co distribution is also sensitive to change of redox condition in the profile.

4.2 Influence of atmospheric inputs on the transfer of alkalis and alkaline earth elements

When primary minerals have been depleted by weathering, the solute flux from precipitation can add substantial mass to soils (Derry and Chadwick, 2007). Particularly in the absence of erosion, mineral dissolution and element leaching depletes mobile constituents derived from rock substrate. And their replenishment by atmospheric deposition leads to dominance of externally sourced ions in near-surface soil horizons. Alkalis and alkaline earth elements, such as K, Na and Sr, are the most active elements and easily removed from the profile during chemical weathering (Nesbitt et al., 1980). The K, Na and Sr concentrations are 12.58, 20.93 and 382.43 μg/g in parent rock, while their concentrations vary from 1.93 to 6.49, 0.16 to 1.08 and 11.57 to 20.33 μg/g in the weathering profile, respectively (Table 1). This shows that nearly all the K, Na and Sr have been removed during extreme weathering in the basaltic weathering profile.

However, the K, Na and Sr concentrations in near-surface soil horizons (0 to 50 cm) are significantly higher than those in the lower profile (Fig. 5). In the *in-situ* basaltic weathering profile, the intensity of chemical weathering in the top section is much stronger than that in the lower section. This can be inferred from the major and trace element records, even though the whole profile has been intensively weathered. Because K, Na and Sr are very easily removed, the concentrations of K, Na and Sr derived from rock in the upper profile should be lower than those of the lower profile. However, the upward increase in the K, Na and Sr concentrations in this profile does not agree with this explanation. Thus, except for being residue of the parent rock, there may exit extraneous inputs of K, Na and Sr.

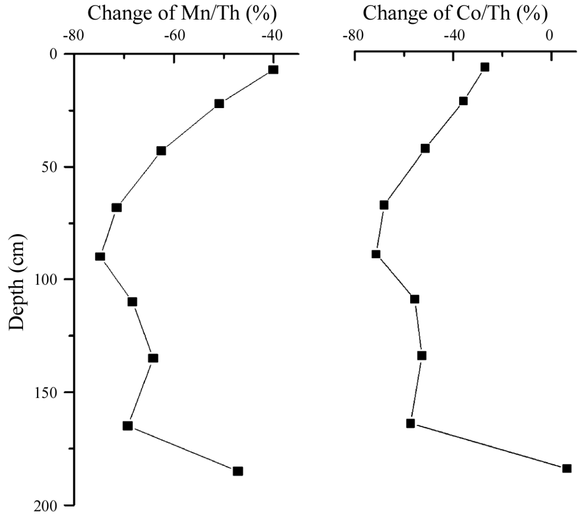

Fig. 4. In-depth variations of the percentage changes of Mn/Th and Co/Th ratios relative to the fresh basalts of soils in Hainan Island.

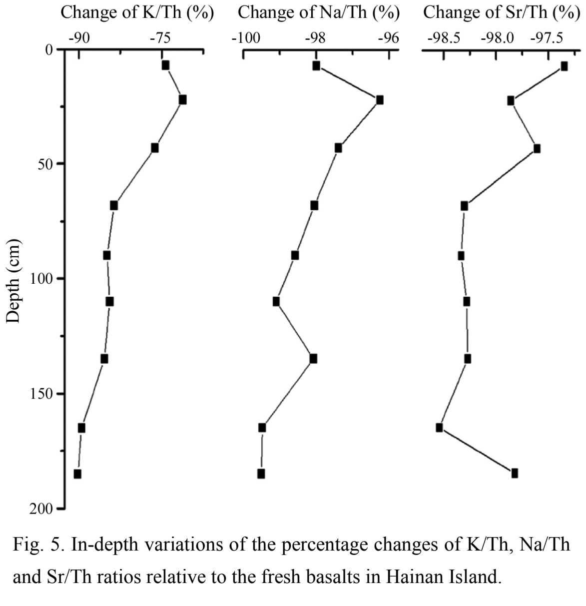

Fig. 5. In-depth variations of the percentage changes of K/Th, Na/Th and Sr/Th ratios relative to the fresh basalts in Hainan Island.

Table 3 Chemical index of alteration (CIA), weathering index (ba) and intensity of chemical weathering (CIW) of the samples in basaltic weathering profile

Depth (cm)	CIW[(a)] (%)	CIA[(b)] (%)	ba[(c)]
7	98.07	93.98	0.06
22	97.76	94.40	0.06
43	98.76	95.78	0.04
68	98.81	96.24	0.04
90	99.36	97.59	0.02
110	99.30	97.70	0.02
135	99.21	97.83	0.02
165	98.12	96.88	0.03
185	98.61	97.78	0.02
Fresh basalt	50.17	48.28	1.07

Note: [(a)] CIW=$Al_2O_3/(Al_2O_3+CaO+Na_2O)\times100$ (Harnois, 1988); [(b)] CIA=$100\times[Al_2O_3/(Al_2O_3+CaO+Na_2O+K_2O)]$ (Nesbitt and Young, 1982); [(c)] ba= $(CaO+Na_2O+K_2O+MgO)/Al_2O_3$.

The losses of K, Na and Sr in soils also can be estimated by the percentage changes of Sr/Th, K/Th and Na/Th ratios relative to the parent rock. As nearly all the K, Na and Sr of the parent rock has been removed during intensive weathering in this profile, the percentage changes of Sr/Th, K/Th and Na/Th ratios relative to the parent rock are significantly negative (Fig. 5). But the percentage changes of these elements ratios are dramatically less negative in the upper profile than in the lower profile. The distributions of the percentage changes of K/Th, Na/Th and Sr/Th ratios relative to the fresh basalts are very similar and all exhibit similar upward increasing trends. Such a pattern indicates that the excessive K, Na and Sr in the upper profile may be imported from extraneous sources.

Extraneous K, Na and Sr inputs have generally been observed in soil profiles (Price et al., 1991; Stewart et al., 2001; Kurtz et al., 2001; Dia et al., 2006). Possible sources for the extraneous K, Na and Sr may be meteoric precipitation (both wet and dry deposits), Sr-laden surface runoff, or groundwater. There is no permanent surface runoff around the profile, and the landform of this profile is a hill, which locates several meters above the drainage for surface runoff formed by rainwater. Moreover, the upper profile is well above the average groundwater level in this region. Thus, surface runoff and groundwater appear not to contribute much extraneous K, Na and Sr to the soils in the upper profile.

Derry and Chadwick (2007) found that the precipitation composition in coastal regions is typically closest to sea salt, and Na^+, K^+, Mg^{2+}, Ca^{2+}, SO_4^{2-} and Cl^- are major ions in marine aerosols. Since most atmospheric water vapor is derived from the ocean, marine aerosols are a major source of solutes in the atmosphere. Considering that the distance from the location of our profile to the South China Sea is less than 10 km (Fig. 1), rainfall from seawater vapor may be the main source for the extraneous K, Na and Sr inputs to our profile. This can be inferred from the fairly high K, Na and Sr concentrations of the precipitation in Sanya City, where Sr concentrations in atmospheric deposition during summer are up to 139 μg/L, and K, Na concentrations are up to 10 and 13.9 mg/L, respectively (Ma et al., 2010). In addition, the study area has a tropical monsoon climate with an annual precipitation of 1826 mm amount, which continuously imports the extraneous atmospheric inputs to the profile, and the consecutively trapping of them by clay minerals may accumulate enough K, Na and Sr to the concentrations of the upper profile. Moreover, Sr is closely associated with Na in the profile, with correlation coefficient between Sr and Na, K and Na concentrations of about 0.73 and 0.86 (N=8). As Na is characteristically from seawater, such correlation suggests that the extraneous Sr and K may come from seawater.

Excluding the possibilities of groundwater and erosion, following evidences indicate that the atmospheric deposition in this region, which enriches in Sr, K and Na from seawater, contribute much extraneous K, Na and Sr to the profile: (1) the remarkable increase in the K, Na and Sr concentrations, (2) dramatically upward increasing trends of the percentage changes of Sr/Th, K/Th and Na/Th ratios in the profile, (3) near the South China Sea and having a tropical monsoon climate with abundant annual precipitation, and (4) both Sr and K are closely associated with Na, characteristically derived from seawater. As a result, atmospheric inputs have a profound effect on the budgets of elements during extreme chemical weathering profiles in tropical regions.

5 Conclusions

The presence or absence of organic complexes, the physicochemical conditions (pH, Eh) of the weathering environment (Patino et al., 2003) and atmospheric inputs (Chadwick et al., 1999; Kurtz et al., 2001) have a profound effect on the mobilization and redistribution of elements during chemical weathering. Elemental geochemistry of weathering profiles developed on Neogene basalts in the tropical Hainan Island, South China, allows us to investigate mobilization and redistribution of major, trace and organic elements during advanced to extreme weathering of basalts.

The results indicate that most of the elements have been mobilized and transferred downwards along the profile by aqueous solution. Strong acid environment and organic matter (OM) can significantly improve the transport of elements. Among all the elements, Th is the least mobile. As for the general conservative elements during incipient chemical weathering, such as Ti, Zr, Hf and Nb, are even quite mobile during extreme weathering in the upper profile. However, these elements behave as conservatively as Th in the lower profile. In addition, the transfer of Fe, Al, Cu and Ni can also be improved by stronger acid environment and dissolved organic matters. Fe, Al, Cu and Ni are mobile during extreme chemical weathering in tropical regions, although these elements tend to be combined with secondary minerals and to be retained in the soil profile in temperate zone.

Nearly all the alkalis and alkaline earth elements, such as K, Na and Sr, have been removed during extreme weathering in the basaltic weathering profile. However, the concentrations of these elements are significantly higher in near-surface soil horizons than these in the lower profile. In addition, the percentage changes of K/Th, Na/Th and Sr/Th ratios relative to the fresh basalts all exhibit similar upward increasing trends, implying that the excessive K, Na and Sr in the upper profile may be imported from extraneous sources. In the absence of erosion and groundwater, because the precipitation composition in coastal regions is typically closest to sea salt, atmospheric deposition in this region, which enriches in Sr, K and Na from seawater, contribute much extraneous K, Na and Sr to the basaltic profile. Therefore, the overall elemental behaviors in this profile suggest that organic matter and atmospheric inputs play a very important role in the mobilization and redistribution of elements during extreme weathering.

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