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The formation of representative lateritic weathering covers in south-central Guangxi (southern China)

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ABSTRACT

The mineralogy and geochemistry have been studied in three representative lateritic weathering covers close to the Tropic of Cancer (Guangxi, South China) with the purpose of studying formation and evolution processes of lateritic covers in this region. The X-ray diffraction and scanning electron microscope analysis results indicate that the contents, particle sizes, shapes and structures of secondary minerals, such as iron and clay minerals, are distinctly different in ferruginous nodular horizon and mottled clay layer of lateritic profiles. The ferruginous nodules are characterized by high concentrations of iron and aluminum and low contents of silicon. The energy analysis suggests that there are element exchanges between hematite crystal and clay minerals. The mass balance calculation results show that there is exogenetic input of iron into lateritic covers, especially within the ferruginous nodular horizon, compared to the bottom layer of the profile. The scanning electron microscope images also confirm that voids and fractures in ferruginous nodules were filled with ferruginous material derived from soil solution. This could be a significant interpretation for the negative correlations between Fe_2O_3 and Al_2O_3. The iron and manganese oxides in ferruginous nodular horizon have an apparent effect on the adsorption and precipitation of cerium. Strontium, compared to other alkali metal and alkali-earth metal elements, concentrates in mottled clay layer. Variation in the He/Gt ratio reflected by the O/Fe ratio in a small ferruginous concretion indicates that climate changes altered aqueous activity of the soil environment. Finally, a model for the formation and evolution of typical lateritic weathering covers in south-central Guangxi, supported by all the data, was proposed.

1. Introduction

Lateritic soils (Ferralsols *sensu stricto*) are considered to be the product of weathering of basement rock under tropical climate conditions. They are rich in Fe and Al, low in silica, chemically acidic, and exhibit a soil profile different from that of other soils (Foos, 1991; McNeil, 1964; Nair et al., 2011; Tardy, 1997; Tardy and Nahon, 1985; Townsend, 1985). Laterization is a function of the soil environment which is related to the fluctuation of the atmospheric climate. The geographic latitude is the most critical of many factors that control the variation of climate. In addition, the level of CO_2 is a key factor (Berner et al., 1983) because intensive volcanic activity can induce localized high CO_2 levels, resulting in a warm and humid climate which intensifies weathering and laterization (Braun et al., 1998). Studies regarding the mineralogy, major element composition, isotopes, fluids and weathering rates have been carried out on soils developed around the Equator (Boeglin and Probst, 1998; Braun et al., 1990, 1998; Girard et al., 1997; Tardy and Nahon, 1985; West and Dumbleton, 1970; Wimpenny et al., 2007). The abundant rainfall, relatively high temperatures, intensive eluviation and generally good drainage are in favor of the development of thick lateritic weathering covers in tropical regions.

The study area is located 1° south of the Tropic of Cancer in the tropical–subtropical transition zone, with a hot and humid monsoon climate. The prominent wet and dry seasons possibly influence the groundwater levels and weathering processes. However, the typical climate in Equatorial regions is wet–tropical or tropical savanna climates which differ from the tropical monsoon climate in terms of the variation of wet and dry seasons and rainfall. The representative lateritic soil covers in our study area developed on Devonian carbonate rocks. They are characterized by a thick ferruginous nodular horizon and variegated clay layer which are similar to the *in situ* weathering of tropical soils in most Equatorial regions (Braun et al., 1990, 1998; Tardy and Nahon, 1985). Although there are many similarities in the regolith profiles there are also significant differences (Horbe and Anand, 2011; Smith, 1996). The iron nodules in the regolith have been reported as a new gibbsite-type bauxite deposit because of its high concentration of Fe and Al and low content of Si and S. The reserves of this deposit account

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for 5% of bauxite resources in China (Liu, 1988; Wang et al., 2011; Zhao et al., 2008). The typical lateritic weathering crust is relatively well developed in the belt from Yulin to Nanning Counties. Lateritic weathering covers are best developed and concentrated in Guigang, Binyang and Hengxian Counties.

The geochemistry and mineralogy of the representative lateritic weathering crusts in south-central Guangxi have been previously studied, although they focused on the high-Fe gibbsite bauxite horizon (ferruginous nodular horizon) with respect to the metallogenic dynamics. Previous studies have shown that essential minerals in iron nodules and concretions are goethite, hematite, gibbsite and kaolinite (Chen et al., 1992, 1997; Li and Liu, 2008; Yang, 1992; Zhou and Mei, 1992). However, mineral micro-morphologies and occurrences are poorly documented. Furthermore, the relationship between iron nodules and lateritic soils, and the formation and evolution of local lateritic profiles (especially regarding the ferruginous nodular horizon) are not yet fully understood.

The purpose of this paper is to investigate the weathering mechanism and evolutionary pattern of lateritic soils. In this study, both X-ray diffraction (XRD) and inductively coupled plasma mass spectrometry (ICP-MS) were utilized to systematically study the migration and enrichment of elements. Moreover, the mineral composition was determined *via* X-ray fluorescence analysis (XRF). In order to get deeper insight into the micro-morphologies of minerals and element composition of samples, scanning electron microscope (SEM) and electron probe micro analysis (EPMA) coupled with energy diffraction spectrum (EDS) were used. Finally, a macro-scale evolution model of lateritic covers and micro-scale formation mechanism of iron nodules is established based on mineralogical and geochemical evidence.

2. Setting

2.1. Geomorphology and climate

The landforms of central Guangxi are primarily karst plains and low hills, with a mean elevation of 50 m. This differs from the mountainous region to the northwest and the coastal plains to the south of Guangxi. The capacious karst plains and hills are commonly covered by a thick weathering product that has been forming since the Tertiary. There are common, non-compacted ferruginous nodular horizons in the upper part of the weathered cover. The construction of the weathering profiles is similar to that of the lateritic profiles in the Equatorial zone described by Braun et al. (2012).

The study area is located south of the Tropic of Cancer and has a humid, tropical monsoon climate (Zhou and Mei, 1992) which is characterized by the alternation of wet (from March to August) and dry (from September to April) seasons. The AAT (average annual temperature) and AAR (average annual rainfall) are 21.5 $\pm$ 5 °C and 1580 $\pm$ 300 mm/yr, respectively. The major vegetation type is evergreen broad-leaf forest which limits the water and soil loss, and induces strong evapotranspiration.

2.2. Geology

The oldest outcrop of strata in study area is Cambrian with shale and sandstone. An angular unconformity exists between the Devonian and underlying Cambrian strata. Ordovician and Silurian strata have been denuded. Carbonate rocks are dominated lithologies of Devonian and Carboniferous that extensively distribute in study area. The Permian and Triassic successions are dominated by carbonate rocks and in conformable contact with the underlying Carboniferous strata. The Cretaceous succession is dominated by red sandstone formation that shares an angular unconformity with underlying strata. Multiphase tectonic movements and various tectonic systems led to complex sedimentary formation, folding, and jointing and faulting. Furthermore, the distribution of the Cenozoic lateritic weathering cover is distinctly controlled by the folds and faults. The Yanshanian intrusive body (Jurassic to early cretaceous), comprised of granodiorite, granite porphyry and quartz porphyry, is exposed in the study area (Zhou and Mei, 1992).

3. Sampling and analytical methods

3.1. Sampling

Three lateritic profiles in south-central Guangxi were investigated in this study; profile XY (N22°51′6.6″, E109°14′12.2″) located in the north of Hengxian County, profile LSX (N22°51′16.3″, E109°14′43.3″) was selected close to profile XY, profile WL (N23°10′59.2″, E109°1′45.7″) near Binyang County (Fig. 1).

The lateritic profiles were studied and divided according to the laterization intensity observed in the physical property, mineralogy and elemental behavior (Fig. 2). The first two study profiles are representative lateritic profiles developed on the Devonian carbonate rocks. Generally, the weathering cover in the study area consists of a thick mottled clay layer overlain by a ferruginous horizon capped by soft clayey and sandy topsoil. However, profile XY lacks the topsoil layer, probably because of intensive denudation. Profiles LSX and XY have the similar structures, so profile LSX was selected for a auxiliary study of profile XY. There is no evidence of significant input from exogenous genesis to the two profiles. However, abundant geochemical and petrographic evidence suggests that samples in different horizons show a succession and homogeneity, thus supporting observations that the weathering cover overlying the two profiles formed by *in situ* weathering and alteration of their parent rocks. Profile WL, which occurs in the Quaternary stratum, differs in that it does not contain the ferruginous nodular horizon. Furthermore, samples in this profile have lower Fe concentration, higher quartz content and a higher weathering maturity.

3.2. Analytical methods

Samples were taken from the representative horizons of each profile according to the stratigraphic order (Fig. 2). Samples were taken and preserve in zip-lock bags (*c.* 2 kg). The samples were air dried, ground in an agate mortar and sieved trough a 200 mesh (74 μm) light sieve. The major element content of bulk rock samples was determined by XRF analysis using a Philips type PW 2404 instrument. The trace element concentrations were measured by ICP-MS (Finnigan MAT Company instrument). The sensitivity of the ICP-MS is 1.0×10^8 cps (1 ppm 1n, U), and the detection limits are Fe: 20 ppt, La: 1.0 ppt and Bi: 2.0 ppt. The mineral composition was determined by XRD, and mineralogical semi-quantitative calculation was based on the lamellae spacing (d value) and X-ray relative intensity (I/I_1). The experimental apparatus was a D/max-2000 model XRD diffractometer, including the instrument standard CuKα target, with settings of 40 Kv, 20 mA, and scanning scope for 2–60°. Thin sections of soil and iron nodules with a carbon coating were observed using scanning electron microscopy (SEM-EDS) and electron probe micro analysis (EPMA-EDS), respectively. The EPMA is manufactured by the Shimadzu Corporation, Kyoto, Japan, and the EDS is a Genesis model manufactured by the EDAX Company, U.S.A. The instrument parameters were: element range from ^{5}B to ^{92}U, electron beam stability was better than 1.5×10^{-3}/H, secondary electron image resolution was 6 nm, minimum moving distance of sample set was 0.01 μm. Both the major and trace elements data were obtained from the Beijing Research Institute of Uranium Geology and the other measurements were carried out at the Institute of Geochemistry, Chinese Academy of Sciences.

3.3. Mass balance calculation

In order to investigate the transportation and enrichment of major and trace elements during weathering and pedogenesis, a method of