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A red clay layer in soils of the Yellow River Delta: Occurrence, properties and implications for elemental budgets and biogeochemical cycles

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ABSTRACT

Clay-enriched layers occurring in deltas are important as they reveal erosion, transportation and deposition of source materials from the basin to the coast. In the Yellow River Delta a red clay layer (RCL) with a thickness of 5–50 cm at 1 m depth in the soil profile occurs in the floodplain area dominated by fluvo-aquic soil derived from Yellow River sediments. The RCL typically has a median grain size of < 20 μm, redness (a*) of > 7, and relatively high contents of illite, calcite and iron oxides. In the Loess-Yellow River sediment-Yellow River Delta soil continuum a regime of weathering, mechanical sorting and dilution by carbonates and silica have been important factors altering the elemental geochemistry. The abundance of secondary minerals and deficiencies of silica and zircon in the RCL suggest that it was separated from a mixed source and was likely derived from highly weathered sediments (such as paleosol) from the basin. RCL samples show substantial accumulation of inorganic carbon with enhancement of the organic carbon content, indicating that increasing organic carbon in alkaline soils may lead to an increase in inorganic carbon in the subsoil. Large variations in elemental ratios have been found in the RCL characterized by excess nitrogen and trace metals and phosphorus deficiency due to adsorption and weathering effects. Implementation of the water-sediment regulation scheme (WSRS) may have altered the sedimentary environment and may have aggravated an elemental imbalance due to the occurrence of the yellow silt layer (YSL)-RCL sequence and thereby impacted biogeochemical cycling in the river-delta-coast continuum.

1. Introduction

Different soil horizons/layers in soil profiles resulting from pedogenesis and/or sedimentation can have contrasting texture, organic matter content, pH, Eh, elemental composition, oxide mineralogy, magnetism or microbial communities and are therefore worthy of study (Xiong et al., 2010; Bockheim and Hartemink, 2013; Li et al., 2018). Clay-enriched layers in soil profiles are important due to their relationship with biogeochemical cycles, environmental pollution and climate change. Clay content can be viewed as a proxy for mineral stabilization of organic matter, an important mechanism in the interpretation of older or longer turnover times of organic matter in the subsoil (Rumpel and Kögel-Knabner, 2011; Schmidt et al., 2011). A clay layer in the subsoil with high site reactivity and specific surface area may also be an important sink for organic pollutants and trace metals (Zhang et al., 2009; Li et al., 2014; Pellegrini et al., 2016). The content and chemical composition of clay fractions are important factors in assessing soil degradation arising from excessive tillage and erosion (Igwe et al., 2009). It is generally believed that clay-enriched layers can develop by clay translocation, in situ formation, and loss of clay from the topsoil (Bockheim and Hartemink, 2013). However, the occurrence of clay-enriched layers in the deltas of large rivers through erosion, transportation and deposition of source materials from basin to coastal zone has been little studied.

Large river deltas and adjacent estuaries are important interfaces between continent and ocean for material fluxes and also large sinks for fluvial materials, anthropogenic pollutants and carbon compounds (Syvitski et al., 2005; Bianchi and Allison, 2009). Changes in the flux and composition of sediment load as a result of climate change and human activities in river basins can be recorded in the deltaic deposits where invaluable historical information can be reconstructed and compared with contemporary changes (Bianchi and Allison, 2009). The

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Yellow River is the second largest river in the world in terms of sediment load with an annual average of 1.1×10^9 t during the past 2000 years (Milliman and Meade, 1983). The large sediment yield is ascribed to both human activities on the Chinese Loess Plateau (CLP) (especially cultivation and deforestation) (Milliman et al., 1987; Ren and Zhu, 1994) and a change in the depositional center of the riverine sediments from the fluvial plain to the coastal area (Ren and Zhu, 1994; Wang et al., 2007). The loess-paleosol sequence in the CLP is believed to be important in containing terrestrial records of paleoclimatic and paleoenvironment changes. In general, the loess sections which have the oldest loess-soil units in the CLP are underlain by reddish clay-silt-sized sediments named the red clay formation (Ding et al., 2001a; Liu, 1985). The loess-red clay units in the CLP have undergone extensive sediment recycling, mixing, and particle sorting processes before deposition and subsequent pedogenic alteration (Liu, 1985; Smalley, 1995; Xiong et al., 2010).

The Yellow River sediment load has decreased by approximately 90% over the past 60 years due to regional climate change (e.g. increased droughts) and human activities (e.g. landscape engineering, terracing and dam construction) (Wang et al., 2016). Moreover, the implement of the water-sediment regulation scheme (WSRS) has greatly modified the sediment texture and sediment composition. The fine-grained sediment exported from the Xiaolangdi Reservoir during the second phase of WSRS is a critical carrier of nutrients and pollutants (Wang et al., 2017). The reduced sediment load and imbalance in elevated elements may have an impact on the quality of coastal wetlands and on the ecosystem (Koiter et al., 2013). Our field investigation found that a red clay layer (RCL) 5–50 cm thick and 1 m deep in the soil profile was widely distributed in the Yellow River Delta (YRD). The soil layers in the YRD can be related to the loess-paleosol sequence in the CLP as a consequence of erosion, transportation and re-deposition. They also have the potential to preserve records of environmental change in the river basin and delta plain (Xue et al., 1995; Saito et al., 2000; Qiao et al., 2011). However, their role in linkage and elemental balance in the river-delta-coast continuum remains poorly understood.

In the present study the elemental composition and main properties of soil profiles within the RCL were thoroughly investigated. The objectives were twofold. First, we aimed to identify the distribution and geochemical characteristics of the red clay layer and elucidate the processes influencing elemental composition in the river-delta-coast continuum. Second, we assessed the capacity to sequester carbon and trace metals and changes in elemental ratios to explore the implications of the RCL for the coastal environment.

2. Materials and methods

2.1. Study area

The study area is located in the Yellow River Delta High-Efficiency Eco-Economic Zone (YRDHEZ), designated a special economic area at national level promoted by the Chinese State Council since 2009. The YRDHEZ is based on the historical Yellow River Delta and coastal areas of north Shandong province (Fig. 1a). It includes 19 counties in 6 municipalities. The YRD is the core area of the YRDHEZ and was formed by deposition of Yellow River sediments as they enter the Bohai Sea. The YRD is important both agriculturally and industrially and is the zone of interaction between the land and the ocean (Li et al., 1998; Fang et al., 2005; Wang et al., 2007). The elevation ranges from about 37 m in the southern hills to < 1 m at the northern and eastern coast (Fang et al., 2005). The area has a warm-temperate continental monsoon climate. The average annual temperature range is 11.7–12.6 °C. The average annual precipitation is 530–630 mm and pan evaporation exceeds 1500 mm (Fang et al., 2005). Approximately 70% of

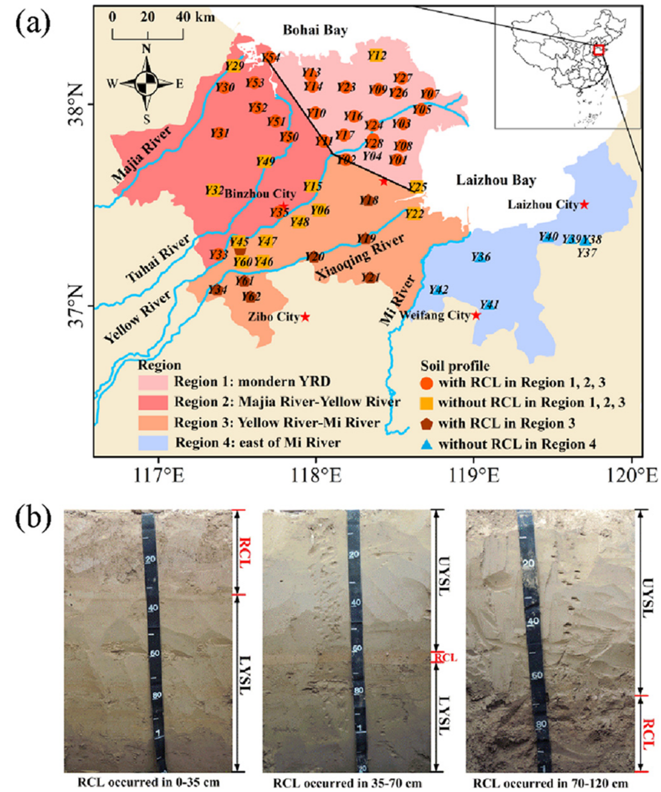

Fig. 1. (a) Map showing the sampling sites and the spatial distribution of the red clay layer (RCL) in the Yellow River Delta High-Efficiency Eco-Economic Zone (YRDHEZ); (b) photographs showing the vertical distribution of the red clay layer and its upper and lower yellow silt layers (UYSL and LYSL).

precipitation occurs during the summer (May–July).

2.2. Soil sampling

Forty-two soil profiles (Y01-Y42) were collected from inland to the coast for chemical analysis and RCL distribution identification and fifteen additional cores (Y45-Y54, Y58-Y62) for RCL distribution identification. Soils were sampled by diagnostic layers to a depth of 1 m. All soil samples were collected using a stainless steel hand auger and then transferred to polyethylene bags. The typical RCL with 5–50 cm thickness in 1 m soil profiles was generally classified as occurring in depth ranges 0–35, 35–70 and 70–120 cm (Fig. 1b). According to the different morphological features, a typical soil profile was divided into three layers, namely the RCL with a reddish brown color and abundant clay and the layers above and below the RCL which had a yellow color and abundant silt and were classified as yellow silt layers (YSL).

2.3. Sample analysis

All soil samples were air dried at room temperature for one week and passed through a 2-mm nylon sieve to remove plant roots and small stones. They were then ground with a pestle and mortar until all particles passed a 0.149-mm nylon sieve. The 2-mm samples were used for the determination of soil grain size, ^{210}Pb activities and for the separation of clay particles. The 0.149-mm samples were used for the determination of color parameters, mineral composition, major elements, trace elements, rare earth elements, iron oxides, and organic carbon (OC), inorganic carbon (IC) and total nitrogen (TN) contents.

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