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Lower Cretaceous paleosols and paleoclimate in Sichuan Basin, China

J. Li [a], X.Y. Wen [b], C.M. Huang [a, *]

[a] Department of Environmental Science and Engineering, Sichuan University, Chengdu, 610065, China
[b] School of Land and Resource, China West Normal University, Nanchong, 637002, China

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ABSTRACT

Abundant Lower Cretaceous (Berriasian–Hauterivian) paleosols have been recognized in the Sichuan Basin, along with the preserved pedogenetic features, e.g., soil horizons, soil structure, root traces and pedogenic nodules. Chemical, geochemical and mineralogical analyses were used to examine the paleosols. These paleosols were classified as Entisols, Inceptisols, Aridisols and Alfisols in terms of the modern soil taxonomic system. Early Cretaceous paleoprecipitation and paleotemperature in the Sichuan Basin were estimated from the degree of chemical weathering for non-calcareous paleosols, and from the depth to the calcic horizon and stable oxygen isotopic composition of pedogenic carbonates in calcareous paleosols, respectively. A temperate semi-arid climate generally prevailed in the Sichuan Basin as a part of the South China Block (SCB) and was controlled by subtropical high-pressure and a rain-shadow effect because the humid air masses from the Paleo-Pacific were impeded by the highlands of the South China Block. Further, several intervals of sub-humid paleoclimate occurred due to strengthened monsoonal circulation in the Early Cretaceous. Using the paleosol barometer, the paleoatmospheric CO_2 levels of the Early Cretaceous are estimated to range from ~120 to ~520 ppmv, with a mean of 305 ppmv. Regional temperature is generally coupled with atmospheric CO_2 concentration and is roughly consistent with the sea level fluctuation.

1. Introduction

The Cretaceous has long been considered a classic typical greenhouse climate period in Earth's history (Bice et al., 2006; Kuypers, Pancost, & Sinninghe Damsté, 1999; Skelton, Spicer, Kelley, & Gilmour, 2003; Tarduno et al., 1998). A detailed record of Cretaceous climate has the potential to improve our understanding of future global climate change. The oceanic response to Cretaceous climate change is relatively well known from oceanic scientific drilling (e.g., DSDP, ODP and IODP); however, the terrestrial paleoclimate reconstruction has been significantly challenged because of the paucity of long-term continuous terrestrial deposits, the difficulties associated with strata dating, and the rarity of reliable paleoclimate proxies (Gröcke, Hesselbo, & Jenkyns, 1999; Hasegawa, 1997, 2003; Heimhofer, Hochuli, & Burla, 2005). A paleosol formed on a landscape of the past (Retallack, 1997, 2001; Ruhe, 1965) is an excellent archive for interpreting and reconstructing the changes in the paleoenvironment and paleoclimate in Earth's history (Blum, 2005; Mack & James, 1994; Sheldon & Tabor, 2009; Tabor & Myers, 2015; Zhou, Retallack, & Huang, 2015). Multiple proxies based on paleosols have been extensively applied to quantitatively reconstruct the climate in the past through careful description and interpretation of various pedogenic properties of paleosols. For examples, paleoprecipitation is calculated using the depth to a Bk horizon below a paleosol surface (Pan & Huang, 2014; Retallack, 2005) and the depth to a gypsic (By) horizon in the profile (Retallack & Huang, 2010), whereas the paleotemperature is estimated using the isotope geochemistry (Dworkin, Nordt, & Atchley, 2005; Hyland & Sheldon, 2013; Nordt, Atchley, & Dworkin, 2003) of calcareous soils developed under arid, semi-arid or sub-humid climates. Furthermore, whole rock geochemistry (e.g., major element weathering indices, trace element ratios and rare earth elements) (Gallagher & Sheldon, 2013; Huang & Gong, 2001; Huang, Retallack, & Wang, 2012; Sheldon, Retallack, & Tanaka, 2002; Sheldon & Tabor, 2009) was utilized to estimate the past precipitation and temperature. Moreover, several soil-order specific climofunctions were established, e.g., the relationships between precipitation and the weathering index or the total Fe content of pedogenic iron-

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* Corresponding author.
E-mail addresses: lj8828@stu.scu.edu.cn (J. Li), wenxy126@126.com (X.Y. Wen), huangcm@scu.edu.cn (C.M. Huang).

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manganese (Fe–Mn) nodules in paleo-Vertisols were used to estimate the paleoprecipitation (Nordt & Driese, 2010; Stiles, Mora, & Driese, 2001).

The long-lived Cretaceous Sichuan Basin in southwest China is an excellent candidate for reconstructing a nearly complete Cretaceous terrestrial sedimentary record (Huang, Retallack, & Wang, 2010; Wan, Chen, & Wei, 2007). Cretaceous paleosols are very commonly preserved in sedimentary strata across the Sichuan Basin (Huang et al., 2010). Here, over 200 Early Cretaceous paleosols surveyed in detail in the northern Sichuan Basin were used to (1) quantitatively interpret the paleoclimate during the Early Cretaceous in the Sichuan Basin; and (2) examine the correlation of regional paleoclimatic variations with the atmospheric pCO_2 levels and global geological events.

2. Geological setting

The Sichuan Basin is a diamond-shaped structural-sedimentary basin located in Sichuan Province, southwest China (Ma et al., 2007; Tan et al., 2011), and covers an area of approximately 1.8×10^5 km^2 (Tong, 1992) (Fig. 1A). The exposed sequence consists entirely of non-marine synorogenic deposits, including lacustrine, alluvial and fluvial sandstone, siltstone, shale and mudstone (Bureau of Geology and Mineral Resources of Sichuan Province, 1991). These strata were divided into four formations (Gudian, Qiqusi, Bailong and Cangxi, in ascending order) and were dominantly distributed in the northwestern Sichuan Basin (Figs. 1 and 2). Overlying the Qiqusi Formation, the Gudian Formation has a maximum thickness of 176 m, is primarily composed of brick-red siltstones and mudstones, and contains well-preserved ostracods. The Qiqusi Formation consists primarily of estuarine mudstone intercalated with beds of siltstone, with a maximum thickness of 440 m. The Bailong Formation conformably overlies the Cangxi Formation and has a maximum thickness of 246 m. The deposits consist of purple and red mudstones and siltstones. The Cangxi Formation has a maximum thickness of 452 m and is dominated by sandstone, with a thin layer of brick red siltstone and mudstone deposited in a fluvial setting with abundant ostracods (Fig. 2).

Because no materials are suitable for dating the paleosols, the ages were inferred from paleomagnetic data and biostratigraphic correlation in the Sichuan Basin (Zhuang et al., 1988; Bureau of Geology and Mineral Resources of Sichuan Province, 1991). The Gudian Formation is assigned to the Hauterivian by Wang, Chen, Guo, Zeng, and Ye (1982) in terms of ostracod assemblages including *Cypridea*, *Ziziphocypris*, and *Jingguella*. Like the Gudian Formation, the strata of the Qiqusi Formation is also rich in ostracods, and based on the regional correlation of ostracods, this formation is referred to the Valanginian (Bureau of Geology and Mineral Resources of Sichuan Province, 1991; Compiling Group of Continental Mesozoic Stratigraphy and Palaeontology in Sichuan Basin of China, 1982). The Bailong Formation was originally considered to be Berriasian in age (Wang et al., 1982), however, Berriasian to Valanginian ages are assumed for the Bailong Formation in light of the paleomagnetic data (Zhuang et al., 1988). The paleomagnetic data and biostratigraphic correlation in the Sichuan Basin show that the Cangxi Formation is referred to the Berriasian (Bureau of Geology and Mineral Resources of Sichuan Province, 1991; Compiling Group of Continental Mesozoic Stratigraphy and

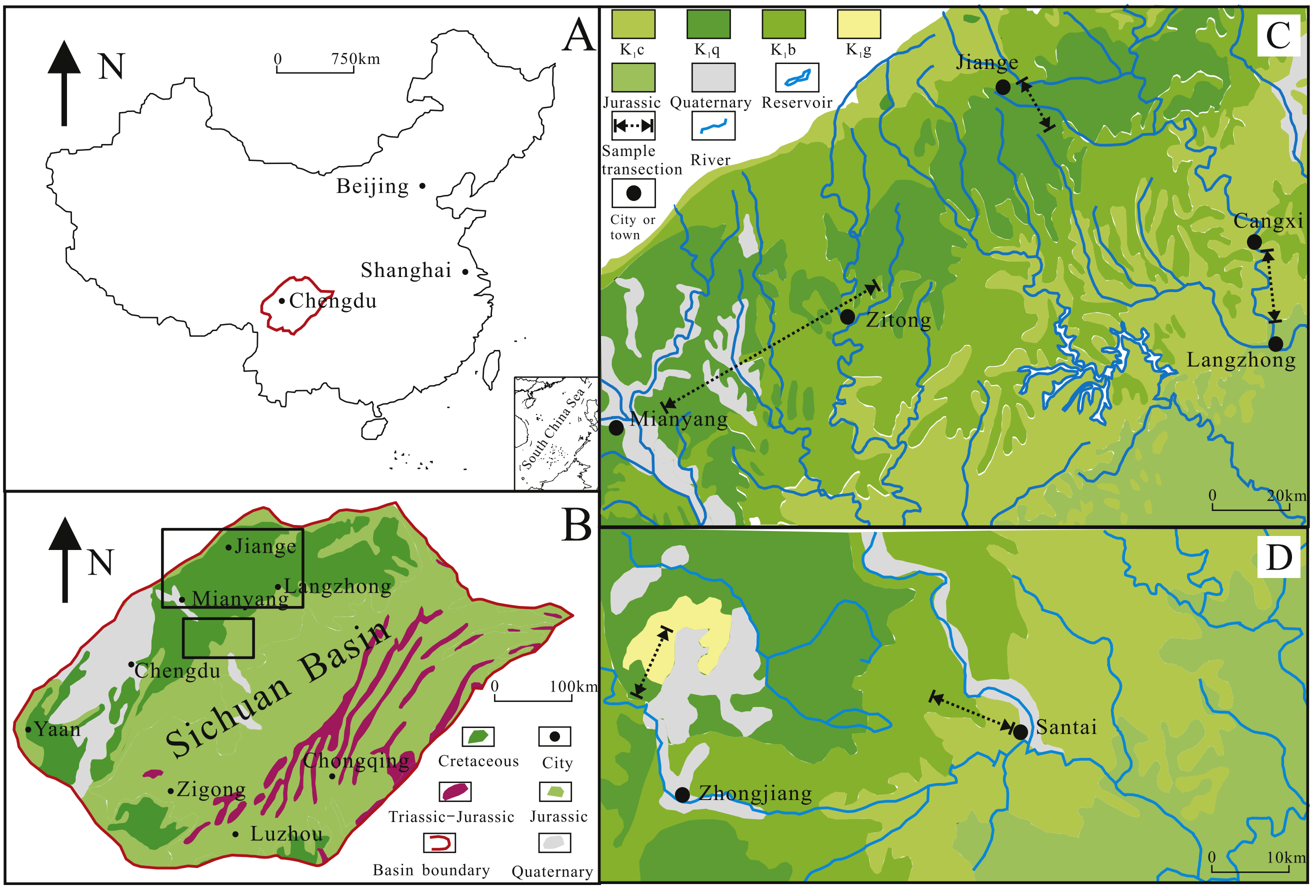

Fig. 1. Sampling locality and geological setting. A, Location of the Sichuan Basin in China. B, Mesozoic strata in the Sichuan Basin. C and D, Locations of the measured transects.