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Mineralogy, petrography and geochemistry of an early Eocene weathering profile on basement granodiorite of Qaidam basin, northern Tibet: Tectonic and paleoclimatic implications

Xing Jian[a,*], Wei Zhang[a], Hanghai Liang[a], Ping Guan[b], Ling Fu[c]

[a] State Key Laboratory of Marine Environmental Science, College of Ocean and Earth Sciences, Xiamen University, Xiamen 361102, PR China
[b] MOE Key Laboratory of Orogenic Belts and Crustal Evolution, School of Earth and Space Sciences, Peking University, Beijing 100871, PR China
[c] Research Institute of Petroleum Exploration and Development (RIPED), PetroChina, Beijing 100083, PR China

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ABSTRACT

Weathering, as an important process in the earth surface system, can be significantly influenced by tectonics and climates over long time scales. Here, we use mineralogical, petrographic and geochemical data of a paleoweathering profile developed on basement granodioritic rocks of northern Qaidam basin, northern Tibet, to reconstruct early Eocene weathering conditions and to discuss how paleoclimates and tectonics dominated the weathering process. The results indicate that neoformed mineral phases in weathering products are dominated by smectite, and the profile has overwhelmingly low chemical index of alteration values (ca. 51–59) and significantly decreasing micropetrographic index values (from 25.0 to 0.2) from bottom to top. These findings suggest that the basement rocks experienced mild chemical weathering but relatively intensive physical weathering. We favor that non-steady-state weathering, in which mechanical erosion rates compare favorably with rates of chemical weathering, prevailed in northern Tibet during the early Eocene. The weathering conditions were likely an integrated response to active tectonism and dry climates at that time. Furthermore, chemical element mobility evaluation demonstrates that most of large ion lithophile elements and light rare earth elements (LREEs) of granodioritic rocks are quite active during weathering and can be easily leached even under mild chemical weathering conditions. Significant mass loss of Al and LREEs in upper weathered samples probably reflects acidic weathering conditions, which were likely due to extremely high atmospheric CO_2 level during the early Eocene. This study, from the unique perspective of weathering process, suggests that intensive deformation and rapid tectonic erosion occurred in northern Tibet during the early Eocene, as a far-field response to the India-Eurasia collision. It also agrees with warm and relatively dry climates, which were likely attributed to the global greenhouse climates and the Paleogene planetary-wind-dominant climate system in Asia, respectively.

1. Introduction

Chemical weathering is a crucial process to control the evolution of the earth surface system, by shaping landscapes, supplying nutrients and trace elements from lithosphere to biosphere and regulating global chemical cycles. Silicate weathering in particular effects the global carbon cycle and thereby global climate through the consumption of atmospheric CO_2 that is eventually stored as carbonates in the oceans (Berner, 1995; Kump et al., 2000). Therefore, chemical weathering of silicate rocks is generally regarded as an important sink of atmospheric CO_2 over geologic timescales and has attracted considerable attention for decades (e.g. White and Blum, 1995; Gaillardet et al., 1999; West et al., 2005; Misra and Froelich, 2012).

It is well accepted that climatic (e.g. temperature, precipitation and runoff), tectonic (e.g. relief, uplift, exhumation and physical erosion) and internally lithological (e.g. ultramafic, mafic and felsic) factors serve as principal controls on weathering process over different time scales (e.g. Raymo and Ruddiman, 1992; Bluth and Kump, 1994; White and Blum, 1995; Riebe et al., 2001; Jacobson et al., 2003; West et al., 2005; Dixon et al., 2012). In this case, paleoweathering study can offer a unique perspective to evaluate and reconstruct tectonic and climatic conditions during the earth's history.

Several approaches can be applied to investigate paleoweathering and associated controlling factors. While elemental and isotopic

* Corresponding author.
E-mail address: xjian@xmu.edu.cn (X. Jian).

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geochemistry data of paleo-seawater have been usually used to reconstruct the global chemical weathering rates during the earth's history (Hodell et al., 1991; Lear et al., 2003; Foster and Vance, 2006; Misra and Froelich, 2012), ancient siliciclastic sediments have been often taken as research objects to evaluate paleoweathering intensity of their source regions (e.g. Nesbitt and Young, 1982; McLennan, 1989; Condie, 1993; Nesbitt et al., 1997; Jian et al., 2013b). However, caution should be exercised while using sediment compositional (e.g. mineralogical and geochemical) proxies to track paleoweathering history, since several factors in addition to chemical weathering might influence sediment compositions during the whole source-to-sink process, such as complicated paleodrainage system, contribution of multiple sources, sorting of detrital minerals and diagenetic alteration (Condie et al., 1995; Fedo et al., 1995; Nesbitt et al., 1996; Garzanti et al., 2010; Jian et al., 2013b). Study on a paleoweathering profile could avoid these effects, which is able to provide in-place data for evaluating weathering conditions during the development of the profile. Hence, paleoweathering profiles have been often concerned and investigated to reconstruct tectonic and climatic history during the earth evolution (e.g. Holland and Beukes, 1990; Nedachi et al., 2005; Driese et al., 2011).

The early Eocene, commonly referred to as the Early Eocene Climatic Optimum (Zachos et al., 2001), was a crucial period during the Cenozoic. The earth then was characterized by high atmospheric CO_2 levels (> 1000 ppmv) (Pagani et al., 2005; Lowenstein and Demicco, 2006) and greenhouse climates (Sloan and Rea, 1995; Zachos et al., 2001, 2008). Meanwhile, the Indian and Eurasian plates collided (at ca. 55–50 Ma), which has been regarded as one of the most significant tectonic events on the earth during the Cenozoic. Subsequently intensive deformation, crustal thickening and uplift generated high-relief topography over a region of approximately 3 million km^2, i.e. the Tibetan Plateau (Yin and Harrison, 2000). It is well known that the early Eocene northern Tibet had regionally dry climates and was in active tectonic settings (e.g. Wang et al., 1999; Sun and Wang, 2005; Yin et al., 2008a; Clark et al., 2010; Zhuang et al., 2011; Yuan et al., 2013; Jian et al., 2018). Although previous studies suggest that intensified chemical weathering of continental silicates prevailed and the ocean environment was drastically perturbed during the Paleocene–Eocene thermal maximum (Robert and Kennett, 1994; Zachos et al., 2005), how the climates and tectonics controlled the early Eocene weathering in the northern Tibet remains elusive questions.

In this study, we focus on a well-preserved granodioritic paleoweathering profile underlain by Cenozoic sedimentary rocks of the Qaidam basin, northern Tibet (Fig. 1), and present mineralogical, petrographic and geochemical data and corresponding interpretations. The aims are to: (1) evaluate weathering conditions in northern Tibet during the early Eocene and (2) explain how the tectonics and paleoclimates influenced surface weathering over a geologic timescale.

2. Geological setting

The Cenozoic Qaidam basin is the largest sedimentary basin in the northern Tibetan Plateau and sits 2.7–3 km above sea level. It is currently located in a very active tectonic background and is bounded by three large mountain ranges (i.e. Eastern Kunlun, Qilian and Altun Mountains) which stand up to 5 km above sea level (Fig. 1A–B). The formation of the current basin-range system is a result of on-going convergence between the Indian and Eurasian plates (Yin and Harrison, 2000; Yuan et al., 2013). Although most structures in the north margin of the plateau have been proven to initiate since the middle Miocene, evidence accumulated recently suggests that widespread deformation and rapid exhumation occurred during the early Eocene (Yin et al., 2008a; Clark et al., 2010; Zhuang et al., 2011; Jian et al., 2018) and the northern boundary of the plateau was established once the India-Eurasia collision commenced (e.g. Yuan et al., 2013 and reference therein).

The current Qaidam basin, as a part of the western China, has dry and cold climates due to high elevations, long distances away from oceans and the Asia monsoon system (Molnar et al., 1993; An et al., 2001; Sun and Wang, 2005). Previous pollen, paleobotanical, sedimentological and geochemical evidence demonstrates that the Eocene Qaidam basin had arid to semiarid climates (Wang et al., 1999; Sun and Wang, 2005; Wang et al., 2011; Guo et al., 2017). Evaporite layers (such as halite and gypsum) are widely distributed in the Eocene sedimentary strata of the basin (Wang et al., 2011; Guan and Jian, 2013; Guo et al., 2017). The regionally dry conditions are commonly suggested to be governed by the Paleogene planetary-wind-dominant climate system, which resulted in a zonal arid band extending from East China to Central Asia (Liu and Guo, 1997; Sun and Wang, 2005; Zhang et al., 2007). Besides, given the global greenhouse climate (e.g. Sloan and Rea, 1995; Zachos et al., 2001, 2008) and the paleo-latitude of ca. 30° N based on paleomagnetic measurements (Wu et al., 1997), the Qaidam basin probably had relatively warm climates during the early Eocene.

The Paleogene strata of the Qaidam basin include the following stratigraphic units: 1) Lulehe Formation (E_{1+2}, ~53.5–~46 Ma); 2) Xia Ganchaigou Formation (E_3, ~46–~35.5 Ma, can be divided into lower and upper parts, i.e., E_3^1 and E_3^2); 3) Shang Ganchaigou Formation (N_1, ~35.5–~22 Ma) (e.g. Jian et al., 2013a; Ji et al., 2017). Both outcrop geological mapping and hydrocarbon exploration drilling data indicate that the Paleogene mainly unconformably lies on Jurassic–Cretaceous sedimentary strata or contacts with pre-Cenozoic basement by faults (Guan and Jian, 2013 and reference therein). Although E_{1+2} strata are widely distributed in the basin (e.g. Yin et al., 2008b), the Maxian paleohigh (Fig. 1C), where the pre-Cenozoic crystalline basement is directly underlain by E_3^1 strata (Fig. 1D; Fig. 2), is supposed to be one of the few exposed areas within the basin area during the early Eocene (Guan and Jian, 2013; Jian et al., 2018). Weathered basement crystalline rocks and overlying E_3^1 sedimentary rocks were fortunately and continuously collected along with the drilling of the hydrocarbon exploration Well MB14 in this area (Fig. 1C–D). Hence, rock cores from Well MB14 provide ideal materials for early Eocene weathering profile investigation.

3. Sample collection and analytical methods

The obtained weathering profile is 3.5 m in length and can be macroscopically divided into four layers with different alteration degrees (Fig. 2), including a 0.4 m saprolite layer (Layer 4), fractured and slightly weathered bedrock (1.1 m, Layer 3), slightly weathered to fresh bedrock (1.5 m, Layer 2) and fresh bedrock (0.5 m, Layer 1). Eight samples were collected along the weathering profile (Fig. 2).

The samples were made to thin-sections for petrographic study. Modal analysis of seven selected samples was carried out using point-counting method and ca. 400 points were counted for each sample. Samples for mineralogical and geochemical analysis were first crushed and then powdered to 200 mesh with an agate mortar.

A Rigaku Ultima IV X-ray diffractometer (XRD) at Xiamen University was used for whole-rock mineral and total clay fraction (< 2 μm) composition analysis. The < 2 μm particles were separated following the Stoke's law and were concentrated using a centrifuge. The resulting pastes were then air-dried on glass slides before XRD scanning. Each sample was continuously scanned under 40 kV, 30 mA, wave length of 1.54 and step width of 0.02° conditions. Scanning speeds were 4°/min and 2°/min for whole rock analysis and < 2 μm fraction analysis, respectively. A MDI jade software was employed for data smoothing, peak picking and phase identification.

Major element compositions were determined by an X-ray fluorescence (XRF) spectrometer at the Research Institute of Uranium Geology (Beijing). The sample powders and lithium metaborate flux were mixed in 1:10 and fused at 1050 °C in a Pt−Au crucible. The well-mixed melt was cooled and then a glass disk was made for XRF analysis. The loss on ignition (LOI) values were obtained by measuring the weight loss after heating the sample at 980 °C.