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Provenance of the upper Miocene–Pliocene Red Clay deposits of the Chinese loess plateau

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A B S T R A C T

A clear understanding of the provenance of late Cenozoic Chinese loess and the underlying Red Clay deposits will shed light on the history and mechanisms of Asian aridification. Although much progress has been made in understanding the source of Quaternary loess on the Chinese Loess Plateau (CLP), the provenance of the underlying upper Miocene–Pliocene Red Clay sequence is largely unknown. Here we present the first provenance history of the Red Clay sequence based on zircon U–Pb ages from the central CLP. Visual and statistical analyses of the U–Pb age populations and comparison with results from potential source regions reveals that (1) the lowermost Red Clay of the late Miocene (depositional age of ∼8 Ma) is likely sourced from the nearby Liupan Mountains and the Qaidam Basin; (2) the middle Red Clay (5.5–4 Ma) of the early-mid Pliocene is sourced mainly from the Taklamakan desert, transported via lower-level westerly winds; (3) the upper Red Clay of the late Pliocene (∼3 Ma) is sourced from mixed areas, although western source materials from middle-northern Tibetan plateau (including Qaidam Desert sediments and materials eroded from the Qilian Mountains) sediments appear to dominate; and (4) the Quaternary loess is also sourced from mixed source regions, albeit with dominant northern CLP proximal desert sediments transported via winter monsoon winds, which in turn may be transported from mountain source regions of the northeastern Tibet and Gobi Altai via major river systems. This long term shift in sources suggests a progressive eastward aridification during the Pliocene in Asia with the specific timing of provenance shifts synchronous with large-scale climatic transitions and Tibetan uplift, demonstrating that Asian desertification is controlled by both factors.

1. Introduction

Aridification is one of the most severe environmental problems humanity has faced over the last century. It is particularly pronounced in northern China: based only on a partial compilation of data, the annual economic loss associated with aridification in northern China is estimated to be above 100 billion Renminbin (¥), equivalent to ca. 16.5 billion US$, since the 1990's (Fu and An, 2002).

More widely, the formation of the arid environment in central Asia has a complex background. Several factors, notably Cenozoic cooling, Tibetan Plateau uplift, and retreat of the Paratethys Sea, are all implicated in causing inland Asian aridification and desertification (An et al., 2001; deMenocal and Rind, 1993; Guo et al., 2002; Li, 1995; Ramstein et al., 1997; Rea et al., 1998; Ruddiman and Raymo, 1988; Zachos et al., 2001). Furthermore, Asian deserts, which lie directly upwind of the Pacific Ocean, have

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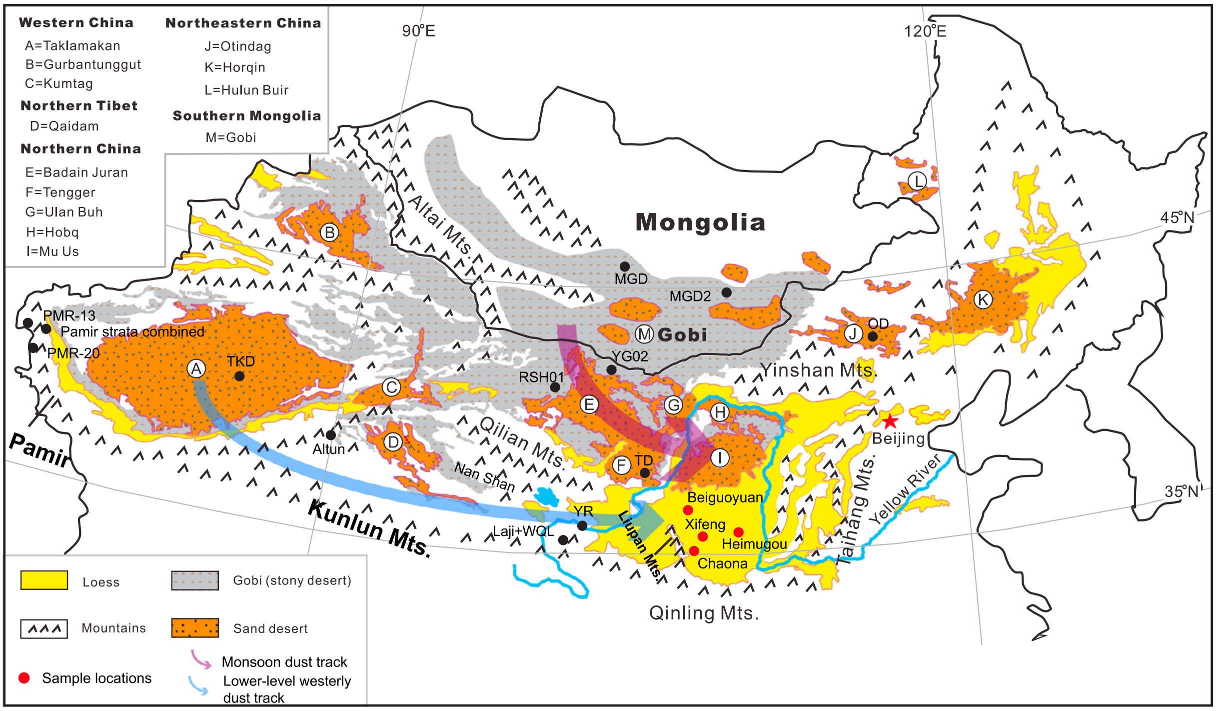

Fig. 1. Loess distribution in northern China and potential source regions and dust transport routes. Revised from Xiao et al. (2012). Approximate sample locations of loess and Red Clay samples (red dots) and source samples (black dots) are shown. Locations of samples from the Qaidam Basin (D) and the Mu Us Desert (I) are not shown due to space limitations. The dot labeled as Laji + WQL indicates the approximate location of 9 rivers draining the Laji and the West Qinling Mountians (Lease et al., 2007). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

been argued to be an active player in controlling climate changes at orbital timescales (Watson et al., 2000). Fe from dust is a limiting nutrient for ocean plankton and higher dust input during glacial periods has been argued to amplify glacial climate cooling by cycling more carbon from the atmosphere to the deep ocean (Watson et al., 2000). Thus, research about Asian aridification is of interest both scientifically and economically.

Preventing contemporary aridification relies on a detailed understanding of its past development to identify the primary causal mechanisms. However, the aridification history in central Asia is largely unknown, mainly because paleoclimate records from inland Asia are sparse and incomplete, making a coherent reconstruction of inland Asian aridification history difficult. For example, paleomagnetic dating of eolian sediments suggests that formation of the Taklamakan desert in the Tarim basin occurred at 5.3 Ma (Sun and Liu, 2006), whereas the oldest eolian sediments in the Gurbantunggut desert of the Junggar Basin were deposited at ∼24 Ma (Sun et al., 2010) (Fig. 1). In the Qaidam Basin (Fig. 1), Pliocene acceleration of aridification has been recognized based on many paleoenvironmental proxy data, including thick-bone fish fossils (Chang et al., 2008), sporopollen records (Wu et al., 2011), stable isotope data (Heermance et al., 2013), and evaporate mineral records (Li et al., 2013a), but when the aridification was initiated in the basin is less clear (Miao et al., 2012). In contrast to these results, direct drilling of the Tengger desert found that dominant eolian facies exist only since ∼1.2 Ma (Li et al., 2013b), much younger than outcrop results in the other inland Asian basins. Aridification in parts of Asia may also have a much longer history, with Cretaceous eolianite sandstone sediments of desert facies underlying large parts of the Mu Us desert and Chinese Loess Plateau (CLP) (Li et al., 1999) (Fig. 1).

Different lines of evidence suggest that Asian deserts are important dust source regions for the CLP (Chen et al., 2007; Sun, 2002; Sun et al., 2001, 2008), although the role of deserts in dust production is controversial, with some authors arguing that processes operating in these regions are not conducive for producing suitable volumes of dust (Lu et al., 2011; Smalley et al., 2005). Despite this, many previous studies have focused on inferring the aridification history of inland Asia based on studying eolian sediments on the CLP (An, 2000; Ding et al., 1999; Fang et al., 1999; Lu and An, 1998; Sun et al., 1997). Two late Cenozoic eolian depositional sequences are well known from the central CLP: the Quaternary loess-paleosol sequence (∼2.7–0 Ma) (Liu, 1985) and the late Miocene–Pliocene Red Clay sequence (∼8–2.7 Ma) (Ding et al., 1999; Song et al., 2001; Sun et al., 1997). The Quaternary loess-paleosol sequence is the most well-studied and understood sequence. Despite this, and while at present there is a consensus that this sequence is eolian, the exact provenance of this sequence is the subject of considerable recent debate (Chen et al., 2007; Chen and Li, 2013; Derbyshire et al., 1998; Guan et al., 2008; Maher et al., 2009; Nie et al., 2013; Pullen et al., 2011; Stevens et al., 2013a, 2013b, 2010; Sun et al., 2008; Xiao et al., 2012). By contrast, in addition to a lack of consensus on sources, no consensus exists as to whether the bottom part of the Red Clay sequence is eolian or water-lain (Ding et al., 1998; Guo et al., 2001; Lu et al., 2001; Miao et al., 2004). Studies arguing for a water-lain environment propose that the lower part of the Red Clay sequence is probably sourced from the nearby Liupan Mountains (Guo et al., 2001). For the upper Red Clay, while there is a consensus that the sediments are eolian, opinions differ as to whether the provenance of the material is western deserts via lower-level westerly winds or northern deserts via winter monsoon winds (Ding et al., 2000; Miao et al., 2004). This severely limits the use of these deposits to shed light on the causes, extent and timing of long term Asian aridification. Note here that we use the term ‘westerly’ wind in the literal sense; to mean wind directed west to east, rather than only upper atmospheric level winds associated with the jet stream at the tropopause. The latter are only one facet of westerly circulation and where needed we have distinguished which we refer to.