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New evidence for the provenance and formation of loess deposits in the Ili River Basin, Arid Central Asia

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ABSTRACT

Loess deposits are thick and widespread along the piedmonts of Arid Central Asia (ACA), however the source (provenance) and processes of formation of these fine-grained aeolian deposits are poorly understood. Here we investigate the provenance and possible distribution mechanisms for loess along the slopes of the Ili River basin, located in northwest China and southeastern Kazakhstan, using a grain-size mixture model and an elemental geochemistry-based source fingerprinting technique. Our results indicate that the Ili loess experiences low rates of sedimentary recycling downstream within the basin piedmont, and are strongly dependent on local geomorphic context. Loess deposits are dominated by proximal sources, indicating short-distance aeolian transport from the Ili River alluvial plains and local proluvial fans. Local sourcing dominated regardless of location within the catchment, although the proportion of fluvial input increases proportionally with increasing distance downstream. Our results suggest that the Central Asian deserts did not act as significant interim storage reservoirs for the loess deposits in the Ili River basin, which contrasts with the popular model for piedmont loess formation across Central Asia. Most likely the relatively enclosed and highly variable basin topography precluded transport from the open desert steppe into the upper Ili River valley. Our study provides the first clear evidence for a genetic link between the Asian high mountains and the loess of the adjacent piedmonts, based on geochemical and grain-size data, with the caveat that the high degree of topographic variability along the Tianshan piedmont likely results in a strongly localized influence on loess formation and accumulation.

1. Introduction

Loess deposits are widespread across the piedmonts of the high mountains of Arid Central Asia (ACA) (Fig. 1a) (Schaetzl et al., 2018). The thick loess deposits of ACA represent promising palaeoenvironmental archives, as has been demonstrated in other regions of the world (Muhs, 2013), but are as yet poorly explored beyond documentation of loess stratigraphy (Ding et al., 2002; Dodonov, 1991; Dodonov and Baiguzina, 1995; Dodonov et al., 1999; Frechen and Dodonov, 1998; Smalley et al., 2006b; Song et al., 2014; Zhou et al., 1995) or the investigation of relative climatic changes recorded in the loess (Dodonov et al., 2006, 1999; Feng et al., 2011b; Fitzsimmons et al., 2018; Song et al., 2018a, 2015, 2018b; Yang et al., 2006; Youn et al., 2014; Zeng et al., 2018).

The endorheic Ili River basin is located in eastern ACA and straddles southeast Kazakhstan and northwest China. The upper part of the catchment (referred to henceforth as the Ili valley) is an intermontane valley surrounded to the north, east and south by the Northern and Southern Tianshan Mountains (Fig. 1b); beyond the Kapshagay dam and north of the city of Almaty, the valley opens to the Kazakh Semirechiye and Gobi Desert steppe northwest (Fig. 1b), and the Ili River forms a large ephemeral delta draining into Lake Balkhash. The topography of the valley floor slopes westward; loess sediments are extensive along the valley slopes (Song et al., 2014).

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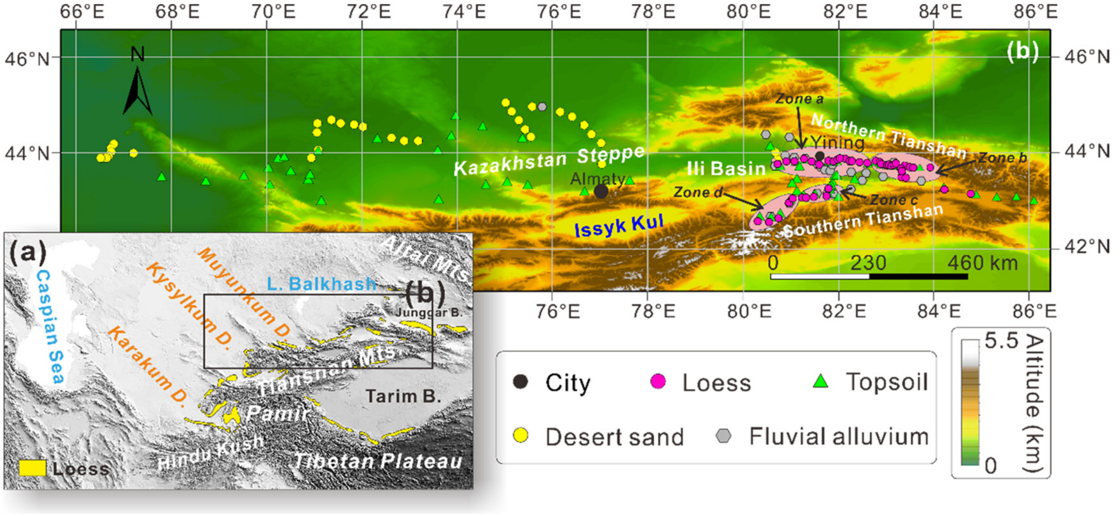

Fig. 1. Location of Arid Central Asia (a) and sampling sites within the Ili valley (b). (a) shows the loess areas in Central Asia. The four pale pink ellipses in (b) represent the geomorphic zones identified in this study. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Identifying the sources of loess, and the mechanisms of loess accumulation, is critical for clarifying the degree to which piedmont loess can be used as a climate archive, as well as for understanding the overall ecological impacts of the dust (Che and Li, 2013; Harrison et al., 2001). The Chinese Loess Plateau (CLP) has formed much of the focus for investigating loess provenance, based on geochemistry, mineralogy, meteorological observation and modeling (e.g. Chen et al. (2007); Hou et al. (2003); Li et al. (2007); Shi and Liu (2011); Sun (2002a); Sun et al. (2013); Xiao et al. (2012)). Although the scale and complexity of the CLP means that researchers are yet to resolve a formation model for the entire region (Chen and Li, 2011; Rao et al., 2006), it is generally agreed that the Alxa arid lands, fed by rivers in the Gobi Altay Mountains to the north and in the Qilian Mountains to the south (Li et al., 2011), provide most of the sediment for the late Pleistocene loess on the CLP (Chen and Li, 2011).

A similar, theoretical model exists for the ACA piedmont loess (Dodonov and Baiguzina, 1995; Machalett et al., 2006b; Smalley et al., 2006b), whereby the vast desert steppe acts as an interim storage for fine-grained particles transported from the mountains by rivers, prior to aeolian transport back onto the lower mountain slopes. However, as yet the provenance of Central Asian loess is largely unknown and mostly inferred. The Ili Basin provides an interesting test case for a targeted study due to its more clearly defined catchment and relationship to the westerly wind trajectories relative to other locations along the ACA piedmonts. Studies so far support the desert-source-model, indicating that the dust is transported from the west of the Ili Basin into the intermontane valley (Li et al., 2012, 2015; Ye, 2000). Sun (2002b) speculated that the $< 20\,\mu m$ fraction of Ili loess is mainly derived from the Sary-Ishikotrau Desert in Kazakhstan, based on observations of geographic context and present-day air circulation systems rather than sedimentological data. Our study addresses this knowledge gap by providing the first dataset aimed at understanding loess provenance and formation in the eastern part of the Ili valley, within the Ili Kazakh Autonomous Prefecture of Xinjiang, China (Fig. 1). We identify distinct source areas based on grain-size characteristics and elemental geochemistry, and analyse the quantitative contributions of different source areas to the Ili loess.

2. Material and methods

2.1 F. ield sampling

We collected a total of 178 bulk sediment samples for provenance analysis, each with a mass of c. 500 g. Of these, 46 loess samples were collected at depths of 50–100 cm from the eastern part of the Ili Valley in China, and 35 desert sand samples were taken from the Kazakh deserts, 29 fluvial alluvium samples from riverbeds, 68 topsoil samples from piedmont slopes and alluvial-proluvial plains at depths of 2–5 cm (Fig. 1b).

The main dust transport trajectories within the Ili valley derive from the western desert part of the Basin and from within the valley itself (Fig. S1). The complex topography of the intermontane valley can influence not only wind trajectories but also the associated transport of aeolian sediments on a local scale, as suggested by Nottebaum et al. (2015a), Qin et al. (2005) and Sprafke et al. (2018). Therefore it is important to consider the geomorphic variability within the valley and its potential influence on loess transport and accumulation. We classified the Ili Valley into four geomorphic zones (Fig. 1b; Supplementary Information): (a) valley plains; (b) higher altitude piedmont; (c) lower altitude piedmont; (d) intermontane valley. Our sampling strategy aimed to cover the full variety of sites and landform types across the Ili Valley.

2.2. Identification of potential source areas

We based our identification of potential source areas on airmass trajectories calculated from present-day data. We employed HYSPLIT (Draxler, 2011; Draxler et al., 1997) to conduct three-day airmass backward trajectories at different heights during the high-frequency dust storm months of March and April (details in Supplementary).

The predominant air mass transport paths are oriented east–west, with additional localized mountain and valley breezes depending on topography (Fig. S1 in Supplementary). We assume that the regions through which air masses flow are the most likely source areas for dust entrainment, and identified areas for sediment sampling on that basis.

2.3. Grain size analysis

Grain size measurements were carried out using published methods (Lu and An, 1997). Carbonates and organic matter were removed with 10 mL of 10% HCl and 10 mL of 10% H_2O_2, respectively. Deionized water was then added and the sample suspension was left for 12 h prior to pipetting, to remove acidic ions. After that, the samples were dispersed with 10 mL of 30% $(NaPO_3)_6$ and placed in an ultrasonic vibrator for 10 min. Finally, the treated samples were measured on a Malvern Mastersizer 2000 hosted at the State Key Laboratory of Loess