From dust to dust: Quaternary wind erosion of the Mu Us Desert and Loess Plateau, China

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ABSTRACT

The Ordos Basin of China encompasses the Mu Us Desert in the northwest and the Chinese Loess Plateau to the south and east. The boundary between the mostly internally drained Mu Us Desert and fluviolacustrine incised Loess Plateau is an erosional escarpment, up to 400 m in relief, composed of Quaternary loess. Linear ridges, with lengths of 10²–10³ m, are formed in Cretaceous–Quaternary strata throughout the basin. Ridge orientations are generally parallel to near-surface wind vectors in the Ordos Basin during modern winter and spring dust storms. Our observations suggest that the Loess Plateau previously extended farther to the north and west of its modern windward escarpment margin and has been partially reworked by eolian processes. The linear topography, Mu Us Desert internal drainage, and escarpment retreat are all attributed to wind erosion, the aerial extent of which expanded southeastward in China in response to Quaternary amplification of Northern Hemisphere glaciation.

INTRODUCTION

The ~750 km (north-south) by ~450 km (east-west) Ordos Basin in China is bound by late Cenozoic rift-flank mountain ranges (Zhang et al., 1998) and encompasses the Mu Us Desert in the northwest and a large portion of the Chinese Loess Plateau in the south and east (Fig. 1). The Yellow River flows northward into the basin along the Yinchuan graben, eastward along the Hetao graben, southward through the eastern Loess Plateau to where it joins the Wei River, and then exits the basin to the east (Fig. 1); it may have followed this course since at least 2 Ma (Craddock et al., 2010; Pan et al., 2011). Much of the deflationary Mu Us Desert exhibits internal drainage and closed topographic depressions (Fig. 2). It exposes mostly Mesozoic bedrock in its western part and variably active and stabilized dune fields above Mesozoic bedrock in its eastern and southern parts (Fig. 1; Li, 2006). In stark contrast, the Chinese Loess Plateau is composed of Earth’s largest accumulation of Quaternary loess and is strongly incised by the Yellow River and its tributaries (Figs. 1 and 2). The loess strata are as much as several hundreds of meters thick and commonly interlayered with paleosols. Loess accumulation occurred primarily during glacial periods when Central Asia was colder and drier, whereas paleosols developed during interglacial periods when the East Asian Monsoon penetrated farther inland (Tungsheng and Zhongli, 1993; Portier, 2007).

There are several motivating questions for this study. What is the nature of the geomorphic boundary between the Mu Us Desert and the Loess Plateau? How did this boundary evolve during the Quaternary? How was the Loess Plateau built? Central Asia became more arid during the Quaternary, concomitant with the increase in Northern Hemisphere ice volume (Tungsheng and Zhongli, 1993), and likely resulted in net desert expansion. Based on an upslope increase in the size and amount of sand in loess along the northern margin of the central Loess Plateau, Ding et al. (2005) proposed that the desert region was located ~200 km farther windward (inland) at the onset of the Quaternary compared to its position during the last glacial period. If correct, this implies a spatial migration in regions characterized by net eolian erosion versus accumulation and a retreating windward margin of the Loess Plateau. To test this hypothesis, we investigated the geology and geomorphology of the Ordos Basin (Fig. 1), with emphasis on mapping landforms in the field and with satellite imagery. We also compared wind patterns resolved from the geomorphology with modern near-surface wind vectors observed seasonally and during dust storms to evaluate our observations within a climatologic context. Our findings demonstrate the importance of wind erosion in sculpting local and regional topography, generating internal drainage, and simultaneously building and reworking a loess plateau.

LOESS PLATEAU WINDWARD ESKER

The spatial transition in the Ordos Basin from bedrock erosion to dunes to loess in the windward (and increased-precipitation gradient) direction (Fig. 1) is observed globally and is an intuitive pattern. Remaining enigmatic, but also widely documented, are abrupt transitions between regions of wind erosion and thick loess accumulation (e.g., Mason et al., 1999). The boundary between the Mu Us Desert and Loess Plateau provides an impressive example. Locally along the western margin of the eastern Loess Plateau, tributaries of the Yellow River mark boundaries between sand dunes of the Mu Us Desert and Loess Plateau strata, and by forming a barrier to sand transport, may contribute to proximal thick loess accumulations downwind.
wind (Mason et al., 1999). In many other places, however, the boundary is an escarpment within loess, hundreds of meters high along the northern margin of the central Loess Plateau (Fig. 2A) and less pronounced but still identifiable in the east (Fig. 2B). There is no indication that the escarpment is a barrier to sand transport or related to Quaternary faulting (Zhang et al., 1998; our observations). The escarpment roughly follows the boundary between internal drainage within the Mu Us Desert and the incised Loess Plateau (Figs. 1 and 2), and in many places forms a drainage divide along which wind gaps are present (Fig. 3B) as a result of stream capture. The Miocene Red Clay Formation, which underlies Loess Plateau strata in many places, is locally exposed in the Mu Us Desert adjacent to extensions of the escarpment (Fig. 3B; Li, 2006; our observations).

**LINEAR LOESS PLATEAU TOPOGRAPHY**

Superimposed on the dendritic incision pattern of the Loess Plateau (Fig. 1) is a small-wavelength (<1 km) linear topographic fabric defined by kilometer-scale-long aligned ridges and parallel valleys (Fig. 3B) in the red shaded regions of Figure 1. The ridges are rilled and the valleys show evidence of fluvial incision. In places the linear topography is prominent and ubiquitous (Figs. DR2A–DR2D), whereas in others it is spatially patchy and/or more cryptic at the 10 km scale, but the overall linear orientation is still resolvable (Figs. DR2E–DR2G). Quaternary loess in the United States locally exhibits similar linear topography; although it is debated whether it is primarily of depositional or erosional origin (Flemal et al., 1972), it is accepted to be wind parallel and the role of wind erosion has been demonstrated (Sweeney and Mason, 2013). The linear topography is developed within the Malan Loess of the last glacial period, and therefore must have (or continued to have) formed since that time.

To document spatial variations in linear loess topography orientation, we mapped orientations in Google Earth™ (n = 2869 localities), spaced across the area of the Loess Plateau where linear topography is evident. A rose diagram of all orientation measurements is shown in Figure 1C, and Figure DR3 shows rose diagrams for ~1° × 1° geographic areas. The red arrows in Figure 1 show the dominant orientation of the linear loess topography, which generally varies <5° at the scale of ~10 km (Figs. DR2A–DR2E) and deviates 5°–10° from a mean value at the scale of ~100 km (Fig. DR3). Exceptions are where there are spatially abrupt variations in linear topography orientation between the two distinct azimuth populations (Fig. 1C). The linear loess topography is oriented 118° ± 14° (mean ± one standard deviation) along the windward margins of the Loess Plateau (Fig. 1). Over a distance of <10 km, the linear topography orientation rotates clockwise to a north-south azimuth (179° ± 11°; mean ± standard deviation) over the central Loess Plateau (Figs. DR2F–DR2H), and the eastern Loess Plateau where it abuts with the Luliang Mountains (Fig. 1). To evaluate whether the wind directions resolved from the geomorphology are consistent
with the modern climatology, we compared them to observed near-surface (10 m height) wind vectors averaged over different seasons from A.D. 1979 to 2010 and over a 6 h time period of maximum wind speed during spring wind-storm events (Fig. 4; Figs. DR4A–DR4G). The seasonal wind pattern most similar to the orientations of the linear topography is that of winter (Fig. DR4D). It shows the first-order clockwise rotation in wind vectors over the Ordos Basin, but with a stronger westerly component over the Mu Us and northern half of the central Loess Plateau. The four spring wind-storm events analyzed were all characterized by northwesterly winds over the Mu Us Desert, consistent with the geomorphology, but variable winds over the Loess Plateau, from northwesterly, to northerly, and even southwesterly to southerly (Fig. 4; Figs. DR4E–DR4G). The wind-storm event of 14 March 2010, however, shows a wind pattern strikingly similar to that indicated by the geomorphology (Fig. 4). Additional comparative studies are needed, but our preliminary analysis implicates modern wind storms in sculpting the eolian geomophology.

**HYPOTHESES AND IMPLICATIONS**

We propose that at the onset of the Quaternary, Loess Plateau strata extended farther across the Ordos Basin (Fig. 2A), consistent with the subsequent ~200 km of Mu Us Desert expansion suggested from loess grain-size studies (Ding et al., 2005). The increase in Northern Hemisphere ice volume during the Quaternary may have brought more frequent and farther southeastward-reaching cold air surges that generated dust storms in Central Asia (Roe, 2009) and concomitantly limited the penetration of the East Asian Monsoon into Central Asia, which in turn would decrease the spatial extent of dust-trapping vegetation cover (Ding et al., 1999). Consequently, regions of former loess accumulation transitioned into regions dominated by wind erosion.

We attribute the development of the linear bedrock ridges and closed depressions in the Mu Us Desert and the Loess Plateau windward escarpment and linear topography to wind erosion. The paleo–Yellow River provided a continuous supply of sand that could be reworked by wind (Stevens et al., 2013). The Loess Plateau escarpment retreated as it was sandblasted while loess continued to accumulate downwind. At a spatial scale greater than that of the scale of regions of closed drainage (kilometers to tens of kilometers), the Mu Us Desert exhibits a subtle decrease in elevation as it approaches the Loess Plateau escarpment (Fig. 2). Here, wind erosion is enhanced because of wind speed acceleration associated with streamline compression over the escarpment (e.g., Jackson and Hunt, 1975) in combination with the higher erodibility of the loess compared to the underlying Red Clay Formation and older bedrock. We propose that through localized scour, wind erosion helped generate internal drainage in the Mu Us Desert at a range of spatial scales (Fig. 2). Where the escarpment forms a drainage divide and exhibits wind gaps (e.g., Fig. 3B), the late Quaternary rate of escarpment retreat exceeded that of headward river incision, such that the upper reaches...
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