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# Accumulation and erosion of aeolian sediments in the northeastern Qinghai-Tibetan Plateau and implications for provenance to the Chinese Loess Plateau

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ABSTRACT

The northern and northeastern Qinghai-Tibetan Plateau (QTP) is regarded as one important source region of the Chinese Loess Plateau (CLP). However, how the fine grain sediments in this region were transported to the CLP remains debatable. In this study, we dated aeolian sediments, alluviums, beach sediments, and sand wedges in the northeastern QTP using optical dating, combined with previously reported ages, explored the aeolian sediment deposition patterns in this region. The dating results shown that aeolian sediments mainly accumulated during the marine isotope stage (MIS) 3 and since the last deglaciation, alluvial sediments mainly deposited during the middle to late MIS 3 (between ~40 ka and 22 ka), and sand wedges formed during the MIS 4 and MIS 2 cold intervals. Based on the sedimentary stratigraphic characteristics and existing optical dating chronologies, we propose that fine grain sediments in the northern and northeastern QTP were eroded and carried to the CLP by westerly wind during last glacial and stadial cold stages. However, during last interglacial and interstadial warm stages, aeolian sediments deflated from western barren lands and deserts were mainly trapped in the northeastern QTP, and some were transported to the Alax arid zone or Yinchuan-Hetao plain by rivers that flow out of QTP, then transported to the CLP by northwesterly Asian winter monsoon (AWM). This cold stage westerly wind transport, warm stage rivers plus AWM transport pattern has existed at least since the late middle Pleistocene.


## 1. Introduction

The Chinese Loess Plateau (CLP) locates in the middle reaches of the Yellow River, and it covers an area of approximately 440,000 $km^2$. It is surrounded by northern Qinghai-Tibetan Plateau (QTP), the Tengger, Mu Us deserts, the Yinshan mountains, the Taihang mountains, and the Qinling mountains (Xiao et al., 2012). The Quaternary loess-paleosol sequences of the CLP were wind-blown silts that derived from arid areas in northwestern China and eastern central Asia (Liu, 1965, 1985). Grain size isolines in the main body of the CLP show a near north-south gradient for both glacial stages and interglacial stages, indicating a dominant north dust source region and approximately north-south dust transport pathway for dust deposits in central and eastern CLP (Yang and Ding, 2008). Recently, geomorphological, stratigraphic, geochemical, and zircon U-Pb chronological studies all regard the northern and northeastern QTP also as one important source region for silts deposited in the CLP (An et al., 2012; Bird et al., 2015; Bowler et al., 1987; Che and Li, 2013; Kapp et al., 2011; Li et al., 2013; Licht et al., 2016; Nie et al., 2014, 2015; Pullen et al., 2011; Stevens et al., 2013). Recent observations find that sand dust storms in QTP occurred frequently during winter and spring seasons every year, and a wide range of mobile dunes and desertification lands in QTP provided plenty of materials for sand dust storms to carry (E C.Y. et al., 2016; Fang et al., 2004; Wang et al., 2008; Yu and Lai, 2012). Because the average elevation of QTP is more than

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3000 m above sea level, fine particles in QTP can be easily raised up into the westerly jet-stream and transported eastward, some can even reached to remote North Pacific region (Fang et al., 2004; Han et al., 2004). Fluvio-lacustrine sediments in the western and central Qaidam basin suffered from strong wind erosion since the Pliocene, implying it might be a potential source region for Quaternary loess in the CLP (Heermance et al., 2013; Nie et al., 2014). A recent quantitative study proposed that sediments in the middle and upper reaches of the Yellow River and fluvio-lacustrine sediments in Qaidam basin contributed more than 75% of the sediments that accumulated in the CLP (Licht et al., 2016).

Debates are ongoing as to how the fine sediments on the northern and northeastern QTP were transported to the CLP. At present, two main views of transport patterns exist within the academic circle; namely, a wind transport pattern and initial hydraulic transport, followed by a wind transport pattern. The wind transport pattern has two modes. The first mode is that fine sediments in the Qaidam basin and the northern QTP to the west were transported to the CLP by the strong westerly jet stream during the glacial stages as the northern hemisphere high latitudes chilled, ice sheets and glaciers expanded, and polar jet streams moved toward the equator (Kapp et al., 2011; Pullen et al., 2011). This resulted in more southerly tracks for dust-generating storms and suppression of the East Asian summer monsoon (EASM) by preventing the subtropical jet stream from shifting northward crosses the QTP (Kapp et al., 2011; Pullen et al., 2011; Vandenberghe et al., 2006). The other mode suggests that a transitional zone existed between the northern QTP source regions and the CLP (Bowler et al., 1987). During the interglacial stages, the transitional zone accumulated the deflated dust from the western source regions. The aeolian deposits in transitional zone were eroded and together with the dust from the western source regions, were transported eastward to the CLP by westerly winds during the following cold glacial stage. This transport mode was repeated, accompanied with Quaternary interglacial-glacial climate cycles. The initial hydraulic transport followed by the wind transport pattern also has two modes. One mode suggests that sediments in the northern QTP were transported to the Alxa arid lands by rivers that drained out of the north flank of the Qilian mountains, then mixed with the sediments derived from the Gobi Altay mountains and fine grain sediments were eventually blown to the CLP by the northwesterly Asian winter monsoon (AWM) (Che and Li, 2013; Li et al., 2013). The other mode proposes that sediments in northeastern QTP were eroded and carried by the upper reach Yellow River, unloaded on the Yinchuan-Hetao plain when the undulating terrain becomes flat, and then locally allocated by the AWM to the Mu Us desert and CLP (Stevens et al., 2013; Nie et al., 2015).

However, neither wind transport pattern nor fluvial plus wind transport pattern are perfect in explaining how the fine sediments transport from northern and northeastern QTP to the CLP. The wind transport pattern is confused when considering how the fine sands and silts were transported across the mountains standing between the northern QTP and the CLP, such as the eastern Qilian mountains, Riyue mountains, Laji mountains, and Liupan mountains. Amit et al. (2014) reported that coarse sands can be abraded into coarse silt grains during the process of downwind transportation, which can partially solve the above confusion. In addition, some sedimentary basins lie between the northern QTP and CLP (such as the Xining basin, Ledu basin, and Lanzhou basin), loess in these basins are younger than 2.2 Ma, at least 0.4 Ma younger than the initial loess accumulation in the CLP (Zeng et al., 1993; Lu et al., 2007; Li et al., 1997; Zhang et al., 2016). This age gap is difficult to understand because these basins lie along the path of dust transport from northern and northeastern QTP eastward to the CLP. The fluvial plus wind transport pattern is difficult to explain where the fine grain sediments in closed basins in the northeastern QTP (such as the Qaidam basin and Qinghai Lake basin) gone, as spectacular yardangs in the Qaidam basin imply that dramatic erosions occurred (Kapp et al., 2011; Heermance et al., 2013). Moreover, some researchers reported that the Yellow River ran through the Lanzhou and Linxia basins ~1.8 Ma ago (Li et al., 1997; Craddock et al., 2010), and the upstream incision into the northeastern QTP may be even younger. The Yellow River cut over the Gonghe basin later than 0.7 Ma, and reached the Tongde basin ~0.5 Ma ago (Craddock et al., 2010; Zhang et al., 2014). Recently, Nie et al. (2015) proposed that the present upper reach of the Yellow River was broadly formed at least ~3.6 Ma ago. The existing controversies on the upper reach Yellow River formation ages made the inference of Yellow River as the main material transporter from northeastern QTP to the CLP throughout the Quaternary more or less doubting.

On the northeastern QTP (located east of the eastern Qaidam basin, and west of the Riyue mountains, i.e., the study area of this study), 1–3 m thick aeolian sediments mantled on top of alluviums, fluvial gravels, beach sediments, or bedrocks (Figs. 1, 2 and S1). The aeolian sediments are loess, aeolian sand, paleosol, and their combinations. Studies have reported that these widespread, surface mantled aeolian sediments accumulated since the last deglaciation (since ~16 ka) (Küster et al., 2006; Lehmkuhl et al., 2014; Liu et al., 2012; Lu et al., 2010; Madsen et al., 2008; Qiang et al., 2013, 2016; Yu and Lai, 2012; Zhang et al., 2015). Sand wedges located immediately underneath the loess and in the upper part of the alluvial gravels were formed between 30 ka and 16 ka (Liu and Lai, 2013; Madsen et al., 2008; Porter et al., 2001), and the upper part of the alluvial gravels were deposited during the middle and late stage of marine isotope stage (MIS) 3 (from 45 ka to 22 ka) (Liu et al., 2010; Madsen et al., 2008; Porter et al., 2001) (Figs. 3c and S1). Some thin loess layers (a few centimeters to 1–2 m thick) interbedded within the alluvial gravels, and they were deposited during the interstadials of the last glacial stage or earlier (Liu et al., 2012; Porter et al., 2001) (Fig. 2c). The aeolian sediment accumulation pattern in this area is different from regions east of the Riyue mountains, where more than one hundred-meter-thick loess-paleosol sequences have been alternately deposited almost continuously since the early Pleistocene (Lu et al., 2007; Zeng et al., 1993). Because this region connects the Qiadam basin and the northern QTP source areas with the eastern CLP, determining aeolian sediment accumulation pattern in this region is useful to understand how the fine sediments in the northern and northeastern QTP were transported eastward to the CLP.

In this study, we first identified and described aeolian sediments within the northeastern QTP through geomorphological and stratigraphic investigations; then, we dated aeolian sediments that mantled on the surface and interbedded within the fluvial gravels or alluvial gravels, alluviums, beach sediments, and sand wedges using optically stimulated luminescence (OSL) dating in several typical sections. Finally, we combined our dated ages with reported OSL ages within the study area by other researchers to explore aeolian sediment accumulation pattern during the last interglacial-glacial cycle. We are also attempt to explore whether winds or rivers, or both were the dominant forces to transport fine grain sediments from the north and northeastern QTP to the CLP. In this study, we provide 37 newly dated OSL ages and use 44 of our previously reported ages (Tables S1 and S2, Fig. S1). In total, this study referenced 361 OSL ages, of which 339 are aeolian sediment ages and 22 are sand wedge, alluvium, and beach sediment ages.