1 *Title:* Climate-driven changes to dune activity during the Last Glacial
2 Maximum and Deglaciation in the Mu Us dune field, north-central China

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4 *Authors:* Zhiwei Xu^{1,2*}, Huayu Lu¹, Shuangwen Yi¹, Jef Vandenberghe³, Joseph A.
5 Mason², Yali Zhou⁴, Xianyan Wang¹

6

7 *Affiliations:* 1. School of Geographic and Oceanographic Sciences, Nanjing
8 University, Nanjing 210023, China; 2. Department of Geography, University of
9 Wisconsin Madison, WI 53706, USA; 3. Department of Earth Sciences, VU
10 University Amsterdam, De Boelelaan 1085, 1081 HV Amsterdam, the Netherlands; 4.
11 College of Tourism and Environmental Sciences, Shaanxi Normal University, Xi'an
12 710062, China

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14 *Corresponding author:* Dr. Zhiwei Xu, zhiweixu@nju.edu.cn

Abstract:

One significant change of terrestrial landscapes in response to past climate change has been the transformation between activity and stability of extensively distributed wind-blown sand dunes. The relations between the dynamics of the aeolian landscape and its drivers are not yet completely understood, however. Evidence of aeolian sand deposition during the Last Glacial Maximum (LGM) is scarce in many mid-latitude dune fields, whereas abundant evidence exists for aeolian sand accumulation during the deglaciation, i.e. after about 15 ka. Whether this contrast actually reflects changes in dune activity is still unclear, making paleoclimatic interpretation uncertain.

Comprehensive field investigation and luminescence dating in the Mu Us dune field, north-central China, demonstrates that aeolian sands deposited during the LGM are preserved as fills in periglacial sand wedges and beneath loess deposits near the downwind dune field margin. The scarcity of LGM dune sand elsewhere in the dune field is interpreted as the result of intensive aeolian activity without substantial net sand accumulation. Increasing sand accumulation after 15 ka, reflected by much more extensive preservation, signals a change in sand supply relative to sand transportation through the dune field. Reduced wind strength and other environmental changes including regional permafrost degradation after 15 ka transformed the dune field state from net erosion to net accumulation; the dunes, however, remained largely mobile as they were in the LGM. Similar diverging patterns of dune sand accumulation and preservation before and after 15 ka in many mid-latitude dune fields imply broad climatic controls linked to the changes in high-northern-latitude forcing.

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38 **Key words:**

39 aeolian processes; arid landscape; deglacial warming; dune activity; dune

40 chronologies; paleoclimate; periglacial processes

1. Introduction

Ecological and geomorphic systems in sand seas and dune fields are sensitive to climate change (*Dong, 2002; Thomas et al., 2005*) and, more recently, human activity. Changes in these systems also have many local environmental and economic impacts and even affect global climate through global biogeochemical cycles (*Jickells et al., 2005*). Knowledge about how dune fields responded to past climate change is important for understanding the interactions between dryland environments and climate, and for predicting future changes in arid lands.

Geomorphologists and Quaternary scientists have often proposed a strong linkage between past aeolian activity and paleoclimatic change at glacial-interglacial timescales (*Liu, 1985; Lancaster, 1997*). Cold, dry and windy climatic conditions during glacial periods should favor strong aeolian activity, with less dune field activity or even full stabilization during interglacial periods under warmer, wetter climates (*Sarnthein, 1978*). It is widely recognized, however, that dune fields in some dry regions are unlikely to have followed this pattern; for example, the Great Basin and Chihuahuan deserts in North America had greater effective moisture during glacial periods, as indicated by pluvial lake formation (*Wells, 1979*).

Since about 1990, major progress has been made in developing chronologies of dune activity that can be used to more adequately test hypotheses on glacial-interglacial change in aeolian activity. Much of this progress has come through the development and application of the optically stimulated luminescence (OSL)

63 dating method, which constrains the depositional time of sand grains (*Aitken*, 1998).

64 The increasing number of OSL ages has also challenged previous understanding
65 of the relation between aeolian activity and paleoclimate over glacial-interglacial
66 cycles (*Chase*, 2009). The dune fields of northern China are a case in point. These
67 dune fields were not glaciated during the Pleistocene; however the period 26-15 ka
68 can be defined as the Last Glacial Maximum (LGM) in northern China, based on
69 climatic and environmental conditions at that time including extensive permafrost
70 development (*Lu et al.*, 2013a; *Zhao et al.*, 2014). As discussed below, the period
71 from 15 ka to 10 ka was marked by major climatic changes in this region, and is
72 referred to here as the deglaciation (DG), in a local sense. There is evidence that
73 degradation of permafrost occurred from the later part of the LGM into the beginning
74 of the DG (*Vandenberghe et al.*, 2004).

75 The LGM climate in northern China was relatively cold, dry, and windy, which
76 should have favored extensive aeolian activity (*Lu et al.*, 2013a); however, dune sands
77 deposited during the LGM have rarely been found. It has been suggested that this
78 presumed period of increased dune mobility during the LGM is simply not well
79 represented by OSL ages from dune sections (*Lu et al.*, 2011), though direct
80 geological evidence for increased dune activity is still rare. In contrast, OSL ages
81 from dozens of sections document extensive aeolian activity in northern Chinese dune
82 fields from the DG into the early Holocene, and during the late Holocene (*Li et al.*,
83 2002, 2007; *Lu et al.*, 2005, 2011; *Sun et al.*, 2006; *Mason et al.*, 2009; *Liu and Lai*,
84 2012; *Yang et al.*, 2013). Given that permafrost degradation approximately coincided

with the LGM to DG transition, it is important to consider the role of permafrost in explaining the scarcity of OSL-dated sand from the LGM, compared to the well-preserved aeolian record from the DG. It is unlikely that permafrost prevented aeolian activity in the LGM of northern China, since it is well-documented in other permafrost environments (*Dallimore et al.*, 1997; *Bateman and Murton*, 2006; *Murton and Bateman*, 2007). However, it is possible that permafrost in some way influenced aeolian sand accumulation and preservation during the LGM.

Records of LGM dune activity are also scarce in many other mid-latitude dune fields, especially when compared with abundant evidence of sand accumulation during the subsequent DG (the timing of the LGM varied globally, but the deglaciation was underway in most regions by 15 ka, if not earlier [*Clark et al.*, 2009]). For example, numerous OSL ages from large dunes of the Nebraska Sand Hills (Central Great Plains, USA) fall between 17 and 14 ka, with few ages from the LGM. This major cluster of ages at 17-14 ka was proposed to represent only the later part of a longer period of dune activity that spanned the LGM (*Mason et al.*, 2011). In the “European sand belt”, relatively scarce sand deposits around the LGM compared to much more common deposition after 15 ka has been attributed to low preservation potential of aeolian sands in the LGM environment (*Kasse*, 1997). *Chase and Thomas* (2006) proposed a somewhat similar explanation, but with an important difference, for dune fields along the western margin of South Africa. There, a cluster of dune ages after 17 ka was interpreted as recording dune field stabilization after widespread but poorly recorded dune activity during the LGM (*Chase*, 2009). A contrasting case is

provided by the Thar Desert of western India, where OSL ages are interpreted as indicating sustained dune activity during both the LGM and DG (*Juyal et al.*, 2006).

The problem of interpreting dune field chronologies spanning the LGM and DG is closely related to a broader issue in the paleoclimatic interpretation of dune field records, which is critical when evaluating the dynamic behavior of aeolian landscapes in response to changes in external forcings. The relationship between OSL age clusters in dune field chronologies and past environmental or climatic change may not be straightforward (*Thomas and Burrough*, 2012; *Telfer and Hesse*, 2013; *Thomas*, 2013; *Lancaster et al.*, 2013), because multiple environmental factors influence how and where the datable sand is preserved, and hence dune field chronologies (*Leighton et al.*, 2014a, b; *Xu et al.*, 2015).

The transition from the LGM through the DG into the Holocene is the largest climatic change within the time represented by OSL chronologies from dune fields; therefore it is particularly important to resolve the problems of interpreting paleoclimatic change from dune field records. The studies of dune activity during the LGM and DG reviewed above all propose that poor preservation, rather than a lack of aeolian activity, may explain why the LGM sands are rarely found, in contrast to sands deposited during the DG and the Holocene. If so, there may be particular geomorphic settings in which aeolian sand from the LGM is in fact preserved, which can be identified through thorough field investigation. Those rare cases of LGM sand preservation may then provide important clues on the environment and aeolian geomorphology of the dune field during the LGM, which can help test current

hypotheses about the generally poor preservation. The aims of this study are to identify settings where LGM sands may be preserved in the Mu Us dune field, to investigate those settings for evidence on the environmental factors influencing sand preservation during the LGM, and to interpret our results in the context of other mid-latitude dune field records spanning the LGM and DG, focusing on evidence for a common response to large-scale climatic forcing.

2. The Mu Us dune field and study strategy

The Mu Us dune field, with an area of $\sim 4 \times 10^4 \text{ km}^2$, is located in the semi-arid region of north-central China (Fig. 1). To its south, the dune field is adjacent to the Chinese Loess Plateau (CLP). Modern mean annual temperature of this dune field is 6-9 °C. Most moisture is brought into the dune field by the summer monsoon, resulting in a decreasing gradient of annual precipitation from 450 to 200 mm towards the northwest. Strong winds, predominantly from the northwest, mostly occur during winter and spring, corresponding to the winter monsoon. Many parts of the dune field are currently undergoing widespread stabilization by increase in vegetation (*Xu et al.*, 2015), but active dunes (mostly barchans, barchanoid ridges and transverse dunes) are still dominant. Provenance studies implicate fluvial channels, floodplains, and local bedrock as dune sand sources (*Dong et al.*, 1983; *Stevens et al.*, 2013), though the modern influx from each of these sources is unknown.

Most dunes in the Mu Us dune field are relatively small (2-20 m high). The

modern dunes are underlain by older aeolian sands, rarely more than a few meters thick and absent in some sections; these were mostly deposited during the DG to the early Holocene, based on previous OSL dating (see Table S1). These older sands, or late Holocene dune sand where older sands are absent, rest directly on Cretaceous sedimentary rock, fluvial deposits or loess. The numerous dune strata sampled from the interior of the dune field rarely contain sand deposited in the LGM. One exception is the BYT section (*He et al.*, 2010). Another occurrence of LGM sands is the ZBT section which is loess-mantled and located at the transition from the Mu Us dune field to the CLP (*Lu et al.*, 2013b). Some lacustrine-mantled sections near the downwind margin of the dune field also contain LGM aeolian sands, with their ages constrained by ^{14}C or TL dating methods (*Zhou et al.*, 2002).

In order to achieve the aforementioned research objective, it was tested whether aeolian sand from the LGM is present in settings where preservation potential of that sand may be higher than in typical dune strata of the Mu Us dune field. Assuming that the dunes migrated toward the south or southeast during the LGM, similar to the present, the sands would most likely be preserved near the dune field's downwind margin where it borders the northern CLP, because of less frequent activation or burial by loess. LGM sands could also be capped by lacustrine sediments, as those reported by *Zhou et al.* (2002). Another potential setting for LGM sands to be preserved is in sand-filled thermal contraction cracks attributed to continuous permafrost during the LGM, occurring both north of and within the dune field (*Dong et al.*, 1985; *Cui et al.*, 2004; *Vandenbergh et al.*, 2004).

3. Methods

3.1. Field investigations

Field investigations were carried out during 2010-2012 both across the Mu Us dune field and in the loess-mantled region of the northern CLP. Outcrops containing aeolian sands were carefully identified, including observations of sedimentary structures and features and their geomorphological locations (Fig. 2). Samples for OSL dating and grain-size analysis were collected from clearly cross-bedded sands of the LP03, LP17, LP2829, EQQ, and XM sections. OSL samples were taken by pushing stainless steel tubes into cleaned vertical sections, sealed with black plastic bags to avoid light exposure. Another two sections (ZJ, BCZ) located near the boundary have thick upper lacustrine sediments, but their lowest layers were also identified as aeolian sands, similar to the cases reported by *Zhou et al.* (2002). Samples from their deepest sand layers were used to determine their ages, by OSL (for BCZ) and ^{14}C dating of soil organic matter (for ZJ). Five new sites with periglacial sand wedges (WS, HZZ1, HZZ2, HJQ, HB12-01) were discovered north of the dune field and within the interior. *Vandenberghe et al.* (2004) found two generations of wedge development due to different periglacial processes (continuous permafrost for the first generation vs. seasonal freezing for the later second generation). Our samples for OSL dating and grain-size analysis were all from the lower part (bottom) of sandy fillings of these wedges, identified as the first generation.

Note that LP03, LP17, LP2829 and XM were previously reported in *Xu et al.* (2013) with preliminary descriptions of their stratigraphies and age estimations, but their complete dosimetric and chronologic results are presented here along with the other eight new sections.

3.2. Laboratory measurements

The preparation and procedures for AMS ^{14}C dating of the sample from the ZJ section were as described in *Wu et al.* (2012), and OxCal 4.0.1 beta software was used for calibration. Grain size distribution of sediment samples was analyzed using a Malvern 2000G laser diffraction particle analyzer after removal of organic matter and carbonate, following a preparation procedure to ensure complete disaggregation of the individual grains (*Lu and An*, 1997). Sand samples were dated using the single aliquot regenerative-dose OSL protocol (*Murray and Wintle*, 2003). Sample preparation was carried out under amber-light conditions. Samples were wet sieved to extract the 90-150 μm fraction, treated with 10% HCl and 30% H_2O_2 to remove carbonate and organic matter, and then with 40% HF for 40 minutes to remove feldspar grains and re-sieved. Purified quartz grains were extracted and considered pure enough when natural and regenerated signal ratios of the infrared stimulated luminescence to the blue-light stimulated luminescence were less than 10%. If not, the 40 minutes etching in 40% HF was repeated. Then, the isolated quartz grains were mounted on 10 mm diameter steel discs with silicon oil. Luminescence signals were measured on a Risø TL/OSL-DA-20C/D reader fitted with blue-green diodes ($\lambda = 470 \pm 30 \text{ nm}$) and

IR-LEDs emitting at 880 ± 80 nm (Bøtter-Jensen *et al.*, 2003). Luminescence was detected by a 9235QA photomultiplier tube through a 7.5 mm thick U-340 filter. To determine the dose rate, concentrations of U, Th and K were measured by Neutron Activation Analysis. Using the revised dose rate conversion factors and water content attenuation factor (Aitken, 1998), the elemental concentration was converted into effective dose rate. The calculation was performed using the 'AGE' program of Grün (2009), including a calculation of the cosmic ray contribution to the dose rate. The ages are listed in Table 1. Another 40 ages from 15 sections, from previous studies (Table S1) were also used for the final analysis.

4. Results

4.1. Sedimentary evidence of permafrost development and aeolian activity

One site of newly identified sand wedges is located in the central part of the Mu Us dune field, while the other four were near 40°N. The host material is mainly grayish or yellowish-green layered sandstone (Fig. 3A), although wedges in the WS section are formed in old loess (Fig. 3B). The well-developed wedges are usually 1-2 m deep, very narrow at the bottom and becoming wider upwards. The top of these wedges is quite flat, and occurs near the present-day ground surface, or is covered by aeolian sands of one to several meters. Several typical characteristics of their sedimentary structures indicate that these are sand wedges, that is, periglacial thermal-contraction cracks with a primary filling of sand (Harry and Gozdzik, 1988;

Murton et al., 2000). The sandstone strata adjacent to the wedges are upturned (Fig. 3A). The fill of the wedges consists of homogeneous sands, but vertically-oriented pebbles could sometimes be found in the wedge bottoms. The wedges have a horizontal spacing of 2-10 m, consistent with a network of large polygons, though the vertical exposures did not allow direct observation of a polygonal pattern. Grain-size analysis of the wedge fills indicates well-sorted, fine or medium sands (Fig. 4). The flat wedge tops may in part reflect wind erosion that flattened any surface topography developed during wedge formation. Consistent with this interpretation, the top of the wedges is often marked by a stone pavement interpreted as an erosional lag (*Vandenberghe et al.*, 2004). As most wedges at all sites are relatively deep (1-2 m), they were not developed in the seasonal frost layer. Thus, the sand wedges are indicators of both permafrost and extensive aeolian activity to the north of and within the dune field during wedge formation.

Aeolian sands interbedded with loess deposits were found to be widespread in the northern CLP, 30-50 km away from the current boundary of the dune field (Fig. 1). These sections in loess-mantled settings (LP03, LP17, LP2829, EQQ, Fig. 2) typically contain a sand layer of one to several meters thick, which is buried by loess and sometimes the Holocene paleosol. The sand occurs high above stream valleys and does not have the form of stream channel or gully fills. Instead, most sections expose an entire, well-preserved dune (Fig. 3C) or an extensive sand sheet. Clear cross-bedding including grainfall lamination indicates formation by downwind migration of dune slip faces, and in some cases wind-ripple lamination, root traces

and burrows can be identified. In the field it is clear that this sand layer is of aeolian origin, as evidenced by its geomorphologic position and sedimentary structure. Beneath the sand layer thick Pleistocene loess is present. Grain-size distributions of these sand layers again support their aeolian origin (Fig. 4). They are well-sorted and finer (mean grain-size of ~70-120 μm) than the sands filling the wedges (~150-400 μm), possibly because they are in a more downwind location. The lowest thick sand layers of ZJ and BCZ sections in a lacustrine-mantled setting are interpreted as aeolian in origin as well. They are fine to medium, well-sorted sands comparable to those in other settings (Fig. 4).

4.2. Ages of aeolian sands in the Mu Us dune field and adjacent region

The OSL ages of sand wedges range from 26 to 15 ka (Fig. 2, Table 1), confirming the formation of permafrost and contemporaneous aeolian activity within the dune field during the LGM. The youngest age of sand within a wedge (15 ka) provides a minimum age for permafrost associated with the LGM in this region. The aeolian sands preserved in the northern CLP where there are no active dunes at present were dated between 23 and 13 ka (LP03, LP17, LP2829 and ZBT sections, Fig. 2). Most ages reside between 23 and 17 ka, indicating extensive dune activity beyond the modern dune field margin during the LGM. The other loess-mantled section (EQQ) from the west of the dune field contains a sand layer dated at 15.6 ka. The aeolian sands from BCZ and ZJ sections in a lacustrine-mantled setting at the boundary of the dune field with the CLP were also dated within the LGM. Among

these dune strata from the interior of the dune field, only the BYT section contains LGM sands (Fig. 2). Other dune strata were mostly younger than 15 ka (Table S1). The thick sand layer from the XM section beyond the dune field to the east is also younger than 15 ka. Nevertheless, the sand wedges with an average age of 20 ka, the aeolian sands in loess-mantled settings with an average age of 18 ka, and those in lacustrine-mantled settings with an average age of 25 ka clearly demonstrate that LGM aeolian activity occurred not only within the dune field but also beyond the dune field to the north, southeast and west.

5. Discussion

5.1. Spatial characteristics of permafrost development and dune activity

Our OSL ages from the sand wedges are consistent with previous TL and ^{14}C results (Fig. 5A), indicating that the southern boundary of continuous permafrost in this part of China during the LGM was at least as far south as 39°N, probably reaching 38°N (Zhao *et al.*, 2014). This cold environment and permafrost associated with the LGM lasted until about 15 ka in the northern part of the Mu Us region. The second generation of wedges ('ground wedges') in this area, attributed to deep seasonal frost rather than permafrost, was formed between 16 and 10 ka (Vandenberghe *et al.*, 2004). Taken together, these ages suggest degradation of continuous permafrost in the northern part of the dune field around 16-15 ka. Warming and permafrost degradation may actually have started earlier toward the

south, between 20 ka and 15 ka, as indicated by a cryoturbation structure in the southern dune field (Vandenberghe *et al.*, 2004), but extinction of permafrost across the dune field most likely occurred after 15 ka.

During the LGM, the boundary between the dune field and CLP shifted 30-50 kilometers to the south and southeast, compared to its present position (Fig. 5B). Thus the LGM, despite the scarcity of LGM OSL ages obtained in previous studies, was actually a time of active dune-field expansion. Most dune sands dated to the DG were deposited inside the dune field (Fig. 5B), indicating that the spatial extension of the Mu Us dune field was actually more restricted after 15 ka, although sands from after that date are much better preserved, yielding many more OSL ages. This contraction in spatial extension indicates weakening in dune activity during the DG, at least near the dune field's south and southeast margins.

5.2. Limited preservation of LGM aeolian sands

Despite evident aeolian activity during the LGM, sands of that age have rarely been found from dune strata in the interior of the Mu Us dune field, as mentioned above. Low frequency of LGM ages is not unique to the Mu Us dune field (Fig. 6A), but appears in many other studies of mid-latitude dune records from Northern and Southern hemispheres, such as the Northern Chinese dune fields (Fig. 6B), the Central Great Plains, USA (Fig. 6D), the European sand belt (Fig. 6E) and dune fields of southwestern Africa (Fig. 6F). Inadequate or biased sampling as suggested for specific settings (Telfer and Thomas, 2007; Stone and Thomas, 2008), might not fully explain

327 this pattern observed in those mid-latitude dune fields.

328 Various region-specific explanations have been proposed for the scarcity of
329 LGM sands. In the European sand belt, surficial re-sedimentation by rain or snowmelt
330 water on top of the impervious permafrost was held partly responsible for low
331 preservation of the LGM sediments (*Kasse, 1997*). This explanation seems unlikely to
332 be applicable to the Mu Us dune field, because climatic conditions there during the
333 LGM were quite dry. Well-exposed sand layers and wedge structures show little
334 evidence of local sediment reworking by water.

335 Older sands are more likely to have been reworked by later aeolian activity or
336 other processes, such as bioturbation (*Halfen et al., 2012*). Such effects must almost
337 always decrease the amount of sand per unit area preserved from older episodes of
338 dune activity, wherever there has been substantial later activation. But despite
339 widespread dune activity in the Mu Us dune field during the early and late Holocene
340 (*Lu et al., 2005; Mason et al., 2009*), sands dated to the DG, just after the LGM, are
341 abundantly preserved. Thus, the low frequency of the LGM sands compared to the
342 much greater frequency of DG sands is not completely explained through sediment
343 reworking in later episodes of activity, but more likely represents poor sand
344 preservation in the LGM.

345 Changes in sand accumulation and preservation should be related to change in
346 major controls on the aeolian system: a) sediment supply, the abundance of source
347 material for the system, b) the transport capacity of the wind, and c) sediment
348 availability, which is the susceptibility of aeolian sediment to transport under specific

set of environmental conditions including vegetation cover, moisture, etc. (*Kocurek and Lancaster, 2004*). In the Mu Us dune field, there must have been an adequate supply of sand to maintain active sand transport during the LGM and to enable aeolian sand expansion to the southeast, but environmental conditions including permafrost could have limited the supply to some extent. Deflation of sand from stream channels and floodplains, both known sources of supply to the Mu Us dunes (*Dong et al., 1983; Stevens et al., 2013*), was probably not directly limited by permafrost. In the cold, dry LGM climate, however, sediment supply from these fluvial sources could have been limited due to diminished fluvial activity and thus a limited supply of readily deflated sand. Weathering of bedrock, the third identified source, would have been limited by cold, dry conditions and permafrost. Even if the climate was generally dry, the short thaw season and in local areas, moist conditions maintained by impeded drainage over permafrost in summer, could have limited the availability of sand from weathered rock or older fluvial sediment outside of active floodplains. An ice-wedge cast previously reported from a low area north of the dune field was attributed to locally moist conditions (*Vandenbergh et al., 2004*).

We propose that net accumulation of sand across most of the Mu Us dune field, was limited during the LGM by a combination of enhanced wind strength, generally high sediment availability because of minimal vegetation cover and dry conditions (though with local limitations), and sufficient but not abundant sand supply. Isolated, fast-moving barchans are observed in certain parts of the dune field today, where the volume of active sand is limited (*Xu et al., 2015*). Similarly, in the LGM, much of the

dune field could have been characterized by small, widely spaced barchans or other wind-transverse dunes migrating rapidly over loess or bedrock substrates, with near-complete recycling of sand and resetting of OSL ages as each dune migrated one wavelength. Indeed, the loess-covered LGM dunes in LP03, LP17, LP2829 and EQQ sections may represent the remains of such migratory dunes, although exposures at these sites do not allow identification of specific dune types. As noted above, the flat tops of LGM sand wedges may often correspond to unconformities, suggesting widespread exposure and aeolian erosion of the substrate between widely spaced LGM dunes. In these conditions, virtually all sand in the dunes would have been continually recycled, with preservation only in locations such as thermal contraction cracks, and also near the downwind margin of the LGM dune field. Near the transition to loess accumulation areas, wind strength decreased but vegetation cover and moisture were likely greater, favoring net sand accumulation while this extension of the dune field was still active.

Low preservation of dune sand during the LGM has also been inferred for the Nebraska Sand Hills dune field of the Great Plains, with older aeolian sands dated to the LGM found buried by loess downwind of the modern dune field (*Mason et al.*, 2011). A similar interpretation of extensive dune activity but poor preservation, because of continuous recycling of dunes driven by strong winds, has been proposed to explain scarce OSL ages from the LGM in dune fields at the western margin of South Africa (*Chase and Thomas*, 2006). These dune fields, when fully active during the LGM, were probably dominated by migratory wind-transverse dunes, e.g.

barchans or transverse ridges (*Chase and Thomas, 2006; Mason et al., 2011*), and they are not in subsiding basins or other settings favoring thick sand accumulation. Thus, the explanation we propose for the Mu Us dune field in the LGM may be much more broadly applicable, though with local variations.

5.3. Changes in dune activity and sand accumulation from LGM to DG

Many mid-latitude dune fields in Fig. 6 of different continents display a similar pattern with significantly higher frequency of sand ages during the DG than during the LGM. Given the interpretation of the sparse LGM record as primarily related to minimal net sand accumulation and poor long-term preservation, the abundance of DG ages (Fig. 6) can be explained by an increase in sand accumulation and preservation potential. If the DG was characterized by lower transport capacity and/or greater sand supply leading to more closely spaced dunes, it seems likely that the basal parts of some dunes would not be completely eroded but would be buried by the next upwind dune. That is, there could be at least minor, patchy, net accumulation of sand. Importantly, DG sands in the Mu Us dune field are typically found in thin beds, much less than the full height of even a small dune (*Xu, 2014*), consistent with this mechanism of preservation. This kind of preservation within a still-active dune field could be favored by environmental conditions such as development of patchy vegetation in low areas with a shallow water table (*Xu et al., 2015*), or greater moisture in unsaturated sands making them more cohesive and enhancing vegetation growth (*Bateman and Murton, 2006*).

Lower transport capacity, greater sand supply, and somewhat lower sand availability within the dune field can all be related to environmental changes associated with the transition from LGM to DG. As discussed in the next section, there is good regional evidence for weaker winds linked to broader climatic change, and the resulting decrease in transport capacity was probably the most important factor that changed in the DG. In the European sand belt, the strongly increased sand accumulation after 15 ka (*Singhvi et al.*, 2001) is considered a result of sediment influx to the aeolian system due to permafrost degradation, specifically through drier surface conditions caused by increased infiltration and a lowered water table. This made a large quantity of sandy source material available for deflation (*Kasse*, 1997). In the drier LGM environment suggested for the Mu Us dune field, the effect of regional permafrost degradation after 15 ka on availability of material at sand sources (e.g. weathered bedrock, older fluvial deposits) would have been much less pronounced; however, it still could have contributed to net sand accumulation. In addition, increased fluvial activity during the DG could have enhanced sediment supply to the dunes, possibly with especially high fluvial sediment fluxes associated with rapid climate shifts during the DG as suggested for the European dune fields (*Kasse*, 1997).

A recent modeling study also shows increased sand accumulation and greater preservation with greater sediment supply, which was reflected in dune chronologies (*Leighton et al.*, 2014b). Previous research has often emphasized the idea that a large increase in sediment supply can lead to initial construction of dune fields. For

example, dune field formation on the Canadian Great Plains during the DG is attributed in part to the abundance of glacial outwash sand exposed as the Laurentide Ice Sheet retreated from this region (*Wolfe et al.*, 2004). In dune fields of the Canadian Great Plains, LGM ages are not recorded because these dunes are mostly in areas that were ice-covered during the LGM; however, the abundance of DG ages from the Canadian dune fields is notable (Fig. 6C). The abundant ages in that time interval are consistent with other mid-latitude settings included in Fig. 6 that were not glaciated or near ice margins, suggesting broader climate controls as well.

Other environmental changes during the DG may also have helped shift the Mu Us dune field from net erosion to net accumulation, through effects on sediment availability within the dune field. Dune activity during the DG was actually restricted or ceased near the downwind margin of the LGM dune field, allowing sands there to be buried by loess, without further encroachment of sand. This change is likely the result of increased stabilization and dust trapping by vegetation (*Tsoar and Pye*, 1987), in response to reduced wind strength and/or greater moisture availability. Either of these changes would facilitate local vegetation growth and reduced sand mobility, within a dune field that remained largely active. Examples of local sand preservation because of increased moisture and/or vegetation have been identified in studies of modern or Late Holocene dunes, such as the formation of residual sands or dune ridges in interdune areas (*Wolfe and Hugenholtz*, 2009; *Xu et al.*, 2015). The case study of glacial and periglacial aeolian activity in Tuktoyaktuk Coastlands, Canada, also highlights that a transition from cold and dry conditions, to less cold and more

moist conditions after about 14 ka switched dune-dominated aeolian activity to sand-sheet aggradation (*Bateman and Murton, 2006*).

More widespread stabilization in the interior of the Mu Us dune field between 15-10 ka is unlikely (*Lu et al., 2005, 2013a; Mason et al., 2009*), because the DG climate in this region with relatively low precipitation could probably not favor enough expansion of vegetation to stabilize the dunes extensively (*Xiao et al., 2004; Lu et al., 2013b*). Thus, fully active dunes were still dominant in the major internal part of the dune field during the DG, as during the LGM. The ages from 15-10 ka represent the later part of an interval of widespread dune activity, as previously proposed (*Mason et al., 2009; Lu et al., 2011*).

5.4. High-northern-latitude forcing of dune activity in mid-latitude dune fields

The Asian monsoon circulation is believed to greatly influence the landscape of northern Chinese dune fields (*Lu et al., 2013a*). Stronger winds related to a stronger winter monsoon would be responsible for dune mobilization, whereas a stronger summer monsoon transports more moisture facilitating vegetation growth and dune field stabilization. Both changes in the winter monsoon and the summer monsoon are closely associated with the Northern Hemisphere ice-sheet (*Ding et al., 1995*), which reached its maximum extent during the LGM (*Clark et al., 2009*). The enlarged ice-sheet intensified the Siberian High and the winter monsoon circulation significantly (*Kutzbach et al., 1993*), but the summer monsoon was weakened at that time (*An et al., 2015*). Therefore, a strong winter monsoon but weak summer

monsoon are major causes for the intensity of LGM dune activity. Strong wind prevailed across the dune field and bare dunes continuously migrated during the LGM, which led to a generally erosional phase in the Mu Us and probably other dune fields of northern China. As a result, dune sands reflecting this period of intensive aeolian activity are scarce and preserved only in specific geomorphic settings.

A variety of evidence indicates that precipitation in northern China was stable at a low level from the LGM through the DG and did not increase substantially until 8 ka (*Xiao et al.*, 2004; *Lu et al.*, 2013b). Therefore, the intensity of the winter monsoon would have been the strongest control on dune activity during the DG. Diminution of the Northern Hemisphere ice-sheet (Fig. 6G), induced by an increase in northern summer insolation (Fig. 6H, *Clark et al.*, 2009), greatly reduced the intensity of the Siberian High and forced its position northward, resulting in a decreasing strength of the winter monsoon. Reduction in wind strength and/or fewer occurrences of dry cold fronts would then be expected since the termination of the glacial maximum, which is confirmed by other paleoclimatic reconstructions (*de Garidel-Thoron et al.*, 2001; *Steinke et al.*, 2011). The grain-size of loess deposits of the CLP also records decreased wind strength during the DG (*Nugteren et al.*, 2004; *Stevens et al.*, 2007). From this independent evidence, weakened wind strength during the DG is proposed to be the most important driver of dune-stabilization near the dune field margin and increased net sand accumulation in the dune field interior. Weakened dune activity owing to reduced transport capacity during the DG was also inferred for the dune fields of South Africa (*Chase and Thomas*, 2006). In the dune fields of the Canadian

Great Plains, the transition from widespread dune field development around 16-11 ka to gradually reduced dune activity afterward was also possibly associated with weakened winds (*Wolfe et al.*, 2004).

Besides weakened wind strength, warming of the Mu Us dune field sufficient to cause complete disappearance of permafrost after 15 ka also corresponds well with the increase in high-northern-latitude temperature (*Johnsen et al.*, 2001). The effect of permafrost degradation on sediment supply and availability in the Mu Us dune field may not be as considerable as the ice-rich permafrost in NW Europe (*Kasse*, 1997). However, locally improved drainage with permafrost degradation could have increased the potential for deflation of sand from some sources, and greater fluvial activity in the DG could have enhanced sediment supply from channels and floodplains. Extensive vegetation growth is unlikely in the Mu Us dune field during the DG due to low precipitation, but it is likely that some localized vegetation patches favored dune stabilization. Thus, despite weaker winds that probably reduced sand transport and allowed some local stabilization, aeolian activity in the interior of the dune field generally continued as a result of sufficient (and possibly increased) sediment supply, increased temperature and low precipitation from 15 to 10 ka. The combined effects of these climatic and terrestrial conditions during the DG maintained dune activity that was initiated in the LGM, but probably with slower dune migration, more patches of stabilized sand, and more sand accumulation, all favoring long-term preservation of sand deposits from the DG.

The transition from LGM to DG dune activity in the northern mid-latitude dune

fields can be linked to changes in Northern Hemisphere ice volume that were triggered by global warming, because sand supply, wind strength and other climatic factors (including moisture availability, etc.) that affect dune field dynamics are all indirectly influenced by variations in ice-sheet size, via the atmospheric bridge (*Lu et al.*, 2010). The generally northward retreat of permafrost distribution during the deglaciation, which possibly influenced sand supply in many areas also evolved with global warming (*Vandenbergh et al.*, 2014). The extensive LGM dune activity in the Mu Us and possibly other northern Chinese dune fields is linked with both high wind strength and deficiency of moisture, in response to the maximum ice-sheet extent at the coldest time of the last glaciation. Activity in other northern mid-latitude dune fields during the LGM, as in the Nebraska Sand Hills (*Mason et al.*, 2011), was probably also linked to cold, dry conditions associated with maximum ice extent. Continued dune activity in the Mu Us dune field during the DG was associated with increased temperature, permafrost degradation, weaker winds and other effects of ice-sheet shrinkage. Other northern mid-latitude dune fields were probably affected by a similar set of environmental changes associated with ice-sheet shrinkage and warming climate in the DG, and they also preserve strong evidence for widespread dune activity at that time. Some of the mechanisms involved were different in specific dune fields, such as those supplied with sediment in the DG directly from freshly exposed glacial sediment. However, the broad similarities of dune field response to ice-sheet shrinkage and global warming in the DG are clear. It is important to note that by modifying atmospheric and terrestrial conditions, modern global warming will

likely have a strong effect on northern mid-latitude dune fields. In the Canadian Great Plains, dunes that were active in the dry cool climate of the Late Holocene are stabilizing with recent warming (*Wolfe and Hugenholtz, 2009*). Other currently stable dune fields may be activated by reduced effective moisture in a warmer climate.

6. Conclusions

Sedimentary and chronological evidence clearly indicating intensive aeolian activity during the LGM were found in the Mu Us dune field. This period of aeolian activity was very sparsely recorded by OSL ages from dune strata because strong winds prevailed in the interior of the dune field; however, LGM aeolian sands were preserved downwind of the present dune field margin or trapped in sand wedges.

Reduced wind strength due to a weakened winter monsoon, possibly greater sediment influx induced by regional permafrost degradation and increased fluvial activity, and more sand colonization by localized vegetation patches in the DG together resulted in a dune field state characterized by continued, widespread activity, but with net sand accumulation in the interior and contraction of the dune field on its downwind side. This dune field state favored more long-term preservation of sand, leading to a high frequency of OSL ages from the DG.

The landscape dynamics of many mid-latitude dune fields during both the LGM and the warming period of the DG are ultimately attributable to changes in Northern Hemisphere ice-volume, though those changes acted through various combinations of changing sediment supply, wind strength, moisture, and temperature. As in the DG,

current global warming will likely bring about significant changes in the state of these dune fields, leading to stabilization in some cases and activation in others.

Acknowledgements

We thank Yanlin Wang, Jie Li, Yingyong Chen, Hanzhi Zhang, Fangying Zhu, Weiming Gong and Sheng Wang for their help in the field, and thanks also go to Chuanbin Yang and Leibin Wang for assistance in laboratory work. We thank Prof. Zhaohui Zhang for providing the ^{14}C age for ZJ section, and Prof. James B. Swinehart for valuable comments on an earlier version of the manuscript. We thank three anonymous reviewers for their constructive comments which substantially improved this paper. This study was supported by the National Natural Science Foundation of China (No. 41472138, 41321062), the Strategic Priority Research Program of the Chinese Academy of Sciences (No. XDA05120704), and the U.S. National Science Foundation (No. ATM-0502489). Z. Xu thanks the Joint-PhD Program from the China Scholarship Council (No.201206190044) and the Dutch-Chinese CAS-KNAW Exchange Program (No. 10CDP036) for supporting overseas studies, and the Graduate Research and Innovation Program of Jiangsu Provincial Department of Education (No. CXZZ12_0042).

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Figure and Table captions

Fig. 1 The Mu Us dune field in northern China and investigated sections. A) World
 map showing geographic locations of northern Chinese dune fields, and other
 mid-latitude dune fields in different continents. a: Northern Chinese dune fields, b:
 dune fields in Canadian Great Plains, c: dune fields in the Central Great Plains, d: the
 European sand belt, e: the dune fields in western South Africa. B) Mu Us dune field
 and Chinese Loess Plateau in northern China. Mu Us dune field is toward the west
 end of the northern Chinese dune field belt, and to its northeast are the Otindag, the

Horqin and the Hulun Buir dune fields. C) Investigated sections in the study area. Outline of the Mu Us dune field is marked by white line. Squares indicate loess-mantled sections, cycles are dune strata, triangles pointing down are periglacial wedges, and triangles pointing up indicate lacustrine-mantled sections. Numbers indicate section ID. 1-9, 11, 13-14 are from this study while 10, 12 and the others are previously reported: 1- HB12-01, 2- HZZ1, 3- HZZ2, 4- HJQ, 5- WS, 6- EQQ, 7- LP03, 8- LP17, 9- LP2829, 10- ZBT, 11- XM, 12- BYT, 13- BCZ, 14- ZJ. Refer to Table S1, supplementary material, for the other sections.

Fig. 2 Stratigraphy and chronology of investigated sections. Numbers correspond to section ID shown in Fig. 1. 10 (ZBT) and 12 (BYT) are from *Lu et al.*, (2013b) and *He et al.*, (2010), respectively, while the others are from this study.

Fig. 3 Photos of typical sand wedges (A, HJQ section, and B, WS section, outlined by red dotted lines) and buried dune (C, outlined by yellow dotted lines). Length of the shovel for scale is about 80 cm. Ages of the wedges are shown in A and B, and age in C indicates average age of aeolian sands in loess-mantled settings.

Fig. 4 Grain size distributions of the sediments. See Table S2 for the grain size data.

Fig. 5 Spatial distribution of aeolian sand ages in the Mu Us dune field. Numbered symbols show sections (with ID) in different settings the same as in Figure 1. Age of

sand layer from each section is labeled nearby. Red color indicates the ages within the LGM while the blue color indicates the ages younger than 15 ka. A) Ages of sands preserved in periglacial wedges, indicated by triangles pointing down. Red dashed line in A indicates the inferred southern boundary of continuous permafrost during the LGM, while blue dashed line indicates the possible southern boundary of continuous permafrost early in the DG. Black triangles in A indicate locations of sand wedges described by other studies, while white triangles reflect other periglacial structures such as cryoturbations. Black lines with number in A indicate modern mean annual temperature of this dune field. B) Ages of the sands preserved in dune strata or loess-mantled sections. Red dashed line in B indicates the expansion of the dune field during the LGM, while blue dashed line indicates the inferred southern and southeastern boundaries of the dune field during the DG. Triangles pointing up show lacustrine-mantled sections, circles indicate dune strata, and squares reflect loess-mantled sections. A white circle in B indicates one dune sequence containing sands older than the LGM. Refer to Table S1 for all ages from these sections, with references.

Fig. 6 Sand age distributions over time in the Mu Us and other dune fields, and potential forcings. A, B, C and D show number of sand ages, while E and F indicate probability of age distributions over time. The grey bars in A and B indicate the ages obtained by this study, while the dark bars are from the other studies. A) Mu Us dune field, B) summary from dune fields in northern China (this study and *Lu et al.*, 2011,

899 2013a), C) dune fields in Canadian Great Plains (summarized by *Halfen and Johnson*,
900 2013), D) dune fields in the Central Great Plains (*Mason et al.*, 2011 and *Halfen and*
901 *Johnson*, 2013), E) European sand belt (*Koster*, 2005), F) dune fields in western
902 South Africa (*Chase and Thomas*, 2006), G) coverage of Northern Hemisphere
903 ice-sheet (*Dyke*, 2004), H) total boreal summer insolation (*Berger et al.*, 2010).

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905 **Table 1** Dosimetry, equivalent doses and OSL ages.

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Figure 1

Figure 3

Figure 4

Figure 5

Figure 6

Table 1

Field Num.	Lab Num.	Burial Depth (m)	Water Content (%)	K ₂ O (%)	U (ppm)	Th (ppm)	De (Gy)	Dose rate (Gy/ka)	Aliquots Num.	Age (ka)
LP03	NJU497	6.5	3.83	1.62±0.05	1.88±0.09	7.76±0.25	51.16±2.53	2.52±0.25	29	20.32±2.25
LP17	NJU535	3.1	5.54	1.78±0.05	2.41±0.10	9.69±0.29	50.03±2.32	2.90±0.30	13	17.25±1.93
LP2829	NJU560	3.3	6.12	1.73±0.05	1.79±0.08	8.08±0.25	58.41±1.37	2.60±0.25	20	22.47±2.20
XM	NJU776	7.0	7.11	1.86±0.06	1.50±0.08	5.98±0.19	34.81±4.83	2.63±0.15	12	13.22±1.99
HJQ	NJU786	4.0	0.36	2.40±0.07	0.52±0.04	1.93±0.10	74.41±5.62	2.94±0.18	12	25.35±2.50
WS	NJU787	2.5	1.40	2.30±0.06	1.16±0.07	4.66±0.16	79.02±8.97	3.16±0.18	12	24.99±3.23
EQQ	NJU826	2.8	4.18	1.52±0.05	1.68±0.08	6.66±0.22	39.64±2.25	2.54±0.14	12	15.62±1.28
BCZ	NJU840	8.2	1.85	1.90±0.06	1.00±0.06	3.39±0.13	62.39±10.42	2.40±0.08	16	26.20±4.53
HZZ1	NJU1053	1.5	1.92	2.50±0.07	1.01±0.06	6.39±0.20	52.47±2.79	3.48±0.20	15	15.10±1.22
HZZ2	NJU1054	1.0	1.47	2.04±0.06	1.20±0.06	7.13±0.23	59.92±2.89	3.13±0.18	10	19.13±1.48
HB12-01	NJU1236	2.0	9.03	1.78±0.06	1.29±0.07	6.37±0.22	42.49±4.13	2.58±0.14	7	16.49±1.86
ZJ	ZJ900	9.0				¹⁴ C age				23.16±0.18