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Large-scale controls on the development of sand seas in northern China

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ABSTRACT

Although sand seas are located in arid regions, given that the proportions of dune areas vary greatly from region to region they are clearly influenced by other factors as well as aridity. This paper discusses the distribution pattern and major features of sand seas and large fields of stabilized dunes in northern China, and demonstrates the main influences on their development. It appears that the availability of onsite loose sediments, not wind strength, is critical to the occurrence of the sand seas on a regional scale. Tectonic, endorheic basins or areas of alluvial fans or forelands of mountain ranges are advantageous to the accumulation of fluvial sediments, and thus are ideal locations of large sand seas in an arid climate. The large dune fields currently stabilized by vegetation were active sand seas during the drier periods of the late Pleistocene and early Holocene. The distribution patterns of Chinese sand seas suggest that the height or size of the dunes in the sand seas are determined more by the availability of sands than any other potential factors. As the sand seas in China account for a large portion of deserts in the middle latitudes of the Northern Hemisphere (Taklamakan is the second largest sand sea on Earth), knowledge of these sand seas' past changes is important for understanding climatic changes in the terrestrial regions of mid-latitudes.

1. Introduction

Although sand seas occur extensively on Earth (Fryberger and Dean, 1979; Lancaster, 1995; Livingstone and Warren, 1996; Goudie, 2002) and on other planetary bodies (Lancaster, 2006; Zimbelman, 2010), the term 'sand sea' has various definitions in the scientific literature. For example, based on studies in the Western Desert of Egypt, Embabi (2004) established two criteria for a sand sea: a) the area of wind-blown sand needs to be >5000 km^2; and b) no less than 50% of this area should be covered by aeolian sand. In the Encyclopedia of Geomorphology (Goudie, 2004), following an earlier definition, the boundary between dune fields and sand seas is set at about 32,000 km^2. That is, only areas of dunes more extensive than that figure can be termed 'sand seas', but whether they are stabilized or active is not clearly stated. Dune fields are variable in area, ranging from two dunes to 32,000 km^2 (Wilson, 1973; Warren, 2004).

This paper follows Embabi's (2004) concept, naming all extensive (>5000 km^2) areas of dunes in western China as sand seas (Fig. 1). The dune fields located in the eastern portion of the desert belt (Fig. 1) cannot be termed sand seas because they consist largely of vegetated, stabilized dunes at the present time. However, they were sand seas when the climate (in terms of precipitation/evaporation ratio) was drier. In order to understand the controlling parameters of the development of sand seas in northern China, these eastern, former sand seas are included in this paper, and the Chinese terminology 'sandy land' is used to describe these vegetated and stabilized dune fields. 'Desert', verbally translated as 'Shamo' in Chinese, is used as an acronym for sand sea in many Chinese publications. This paper aims first to set up an inventory of the sand seas in China, then analyzes the key factors causing the current distribution pattern of the sand seas, and finally provides an update of knowledge relating to the late Quaternary changes of these sand seas.

2. Major features of the sand seas in northern China

The sand seas and sandy lands in China are the eastern portion of the Asian desert belt which extends east from the desert basins of Kazakhstan, Uzbekistan and Turkmenistan to the west at the middle latitudes. The Helan Mountains, stretching N–S (~106°E), act as a boundary between the arid and semi-arid zones. Six of the seven sand seas of China are located west of this mountain range, but four of the five large sandy lands of China occur east of the

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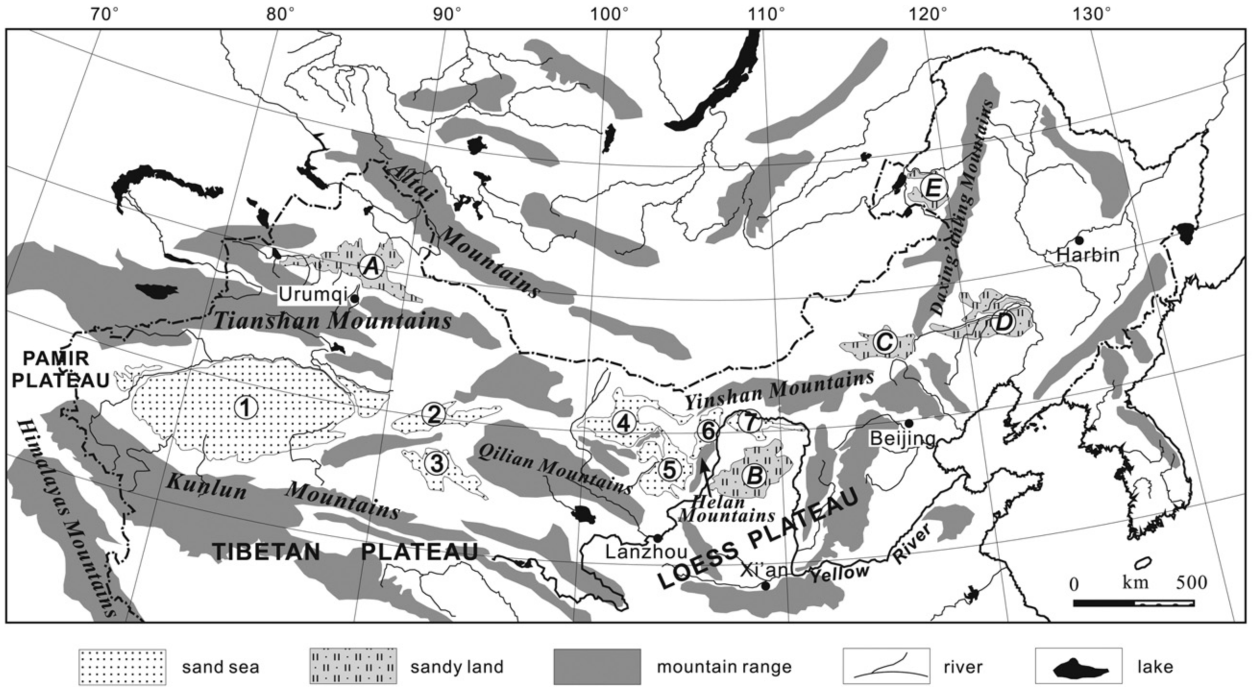

Fig. 1. Distribution of sand seas (sandy desert; 1, Taklamakan; 2, Kumtag; 3, Chaidamu; 4, Badain Jaran; 5, Tengger; 6, Wulanbuhe; 7, Kubuqi) and stabilized dune fields (sandy land; A, Gurbantunggut; B, Maowusu; C, Hunshandake; D, Horqin; E, Hulunbeier) in northern China.

range (Fig. 1, Table 1). Although located in the latitudes of the westerlies of the Northern Hemisphere, northern China lies under the strong influence of a well-developed high-pressure system situated over mid-Siberia and Mongolia during the winter months, and thus winds from the north, the so-called winter monsoons, are dominant. In summer, this desert belt is affected by tropical air masses from the south, i.e., the summer monsoons, and the impact is stronger in the east than in the west due to the different distance to the oceans. As a result, a large portion of the limited precipitation in the west part of the desert belt comes from westerly winds, but the sand seas in the central part (Badain Jaran and those located to its east) are slightly influenced by summer monsoons also.

2.1. Modern sand seas

The Taklamakan (Taklimakan or Takelamagan) Sand Sea is 337,600 km^2 in area, the largest desert in China. About 85% of the sand sea is covered by mobile dunes (Figs. 2 and 3) which reach heights of over 100 m. On the map of aeolian landforms in the Taklamakan Desert, the dunes are divided into ten different types: compound megadunes; compound longitudinal dunes; compound barchan dunes; barchan chains; dome-shaped dunes; pyramid dunes; scale-shaped dune groups; longitudinal dunes; net-like sand accumulations, and sand mounds (Institute of Desert Research, CAS, 1980; Figs. 2 and 3). Zhu et al. (1980, 1981) described most of the dunes as longitudinal, with their directions of movement parallel to the direction of onsite prevailing winds. The longitudinal dunes reach several km in length with a maximum of 12 km. In some more recent publications (for example, Wang et al., 2003) these types of dunes are termed ‘complex linear dune’. It was proposed that the longitudinal dunes of the Taklamakan often originated from barchan dunes. One of the horns of barchan dunes may be elongated, with the merging of the long horns of different dunes being responsible for the formation of the longitudinal dunes (Zhu et al., 1981).

Table 1
Area of sand seas and fields of stabilized dunes (sandy land) in northern China (from Zhu et al., 1980; Wang, 1990; Chen, 1994).

	Area (km^2)	Active dunes (%)	Vegetation coverage (%)
Sand Sea			
Taklamakan (Taklimakan)	337,600	85	–
Kumtag	19,500	–	–
Chaidamu (Tsaidam, Qaidam)	34,900	23	–
Badain Jaran	49,200	83	–
Tengger	42,700	66	–
Kubuqi (Hobq)	16,000	80	–
Wulanbuhe (Ulan Buh)	9900	39	–
Sandy Land			
Gurbantunggut	48,800	3	–
Maowusu (Mu Us)	32,100	–	40–50
Hunshandake (Otindag)	21,400	2	30–50
Horqin (Keerqin)	42,300	10	20–40
Hulunbeier	7200	–	30–50

Note: - no data.

With an area of ca. 49,200 km^2, the Badain Jaran Desert is actually the second largest sand sea in China. Two properties of this sand sea deserve particular attention. First, the dunes are the highest not only on Earth but also higher than all other dunes found so far on other planetary bodies (Lancaster, 2006; Zimbelman, 2010). In the southeastern part of the desert, the dunes are often 200–300 m high with a maximum of 460 m, but the real thickness of sand is not yet known because of the potential occurrence of hilly bedrocks beneath the dunes. The dunes are mainly compound forms and dune chains, consisting of multiple dune generations arising from climate fluctuations (Yang et al., 2003). Earlier they were named as compound, crescentic (large barchanoid) ridges (Breed and Grow, 1979). The ridges are spaced an average of 2.9 km apart according to measurements of crescentic segments on Landsat images (Breed and Grow, 1979). Another distinctive feature of this desert is the occurrence of a large number of permanent lakes in the inter-dune lowlands (Fig. 3b). The recharge of these lakes has been controversially debated among researchers. Melt-water from the Qilian Mountains, ~500 km to the southwest, was reported to maintain the dunes and to recharge these lakes through

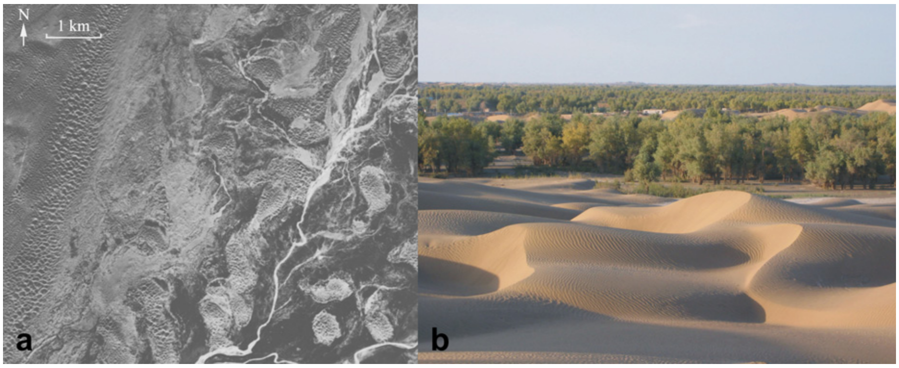

Fig. 2. (a): Scale-shaped dunes (left part of the air photo) and dome-shaped (right portion of the air photo) in the lower reaches of the Keriya River, Central Taklamakan. On this photo, both the earlier courses (left side) and the modern courses (right side) of the river are visible. The dome-shaped dunes were formed while the river flowed through the earlier dune chains. (b): Photo, viewing westwards, taken from the ridge of a dome-shaped dune (30 m high) in the left photo, showing the dune body covered by secondary dunes and the dense trees in the inter-dune areas due to flooding water.

a subsurface fault (Chen et al., 2004). Others suggest that the recharge of these lakes is mainly from local and regional rainfall (Yang and Williams, 2003; Yang et al., 2010).

The Tengger Desert located in the western foreland of the Helan Mountains is the third largest sand sea in China. Two thirds of this sand sea is occupied by dunes, 93% of which are active, while vegetated lake beds and basement hills are common in the remaining area of the sand sea. Plants such as *Ephedra* and *Artemisia* grow quite densely in some of the inter-dune lowlands. The main types of the dunes are net-shaped in the interior part of the sand sea, with long dune chains on the margins. Under the prevailing winds from the northwest, the dunes tend to move southeastwards (Zhu et al., 1980; Yang et al., 2004).

The Desert in the Chaidamu Basin (Tsaidam, Qaidam) is usually regarded as the fourth largest sand sea in China, but it should be clarified that two thirds of this desert consists of erosional landforms (yardangs) and desert pavements. Dunes occur mainly in the marginal areas, dominated by nebkas, barchans, longitudinal dunes and dune chains, mostly just 5–10 m in height with a maximum up to 50 m. The yardangs may reach a maximum height of 50 m also, and a length of several km, particularly in the northwestern part of the basin. The desert in the Chaidamu Basin was classified as being on the second level of aeolian relief in China, as the elevation here is generally between 2600 m and 3000 m asl. Dunes in the intermontane basins of the Tibetan Plateau, at 4300–4900 m asl, are in the third level of aeolian relief (Jäkel, 2002). These dunes develop in areas of mountain permafrost and occur on former alluvial fans and lacustrine terraces. These types of dunes cannot form a sand sea because they are isolated from one another. The largest dune field is 35 km long and 7 km wide (Jäkel, 2002).

The Kumtag Desert is the fifth largest sand sea in China. The morphology of this desert is characterized by the co-existence of dunes, desert pavements, wind-deflated fields, denuded hills and saline plains. The dunes occur mainly in the southern part of the desert, particularly on the flat slopes and forelands of the mountains, parallel to the direction of the predominant winds (roughly N–S), reaching a height of 10–20 m (Zhu et al., 1980). In aerial photos some of the dunes appear feathery, due to the strong contrast in albedo between dunes and inter-dune lowlands (Dong et al., 2008). Rivers with headwaters in the southern mountains have formed deep gorges in this sand sea.

The Wulanbuhe (Ulan Buh) Desert, located in the eastern margin of the Alashan Plateau and on the western bank of the Yellow River, is nearly 10,000 km^2 in extent, the smallest sand sea in China. The dunes occur mainly in the south, adjacent to the Yellow River, and reach a height of 5–20 m in general and a maximum of 50–80 m. Each portion of the active, semi-stable and stable dunes accounts for one third of the total dunes (Zhu et al., 1980; Yang et al., 2004).

The Kubuqi (Hobq) Desert is the only sand sea occurring east of the Helan Mountains (Fig. 1), in a semi-arid environment according to climate classifications in China. Mean annual precipitation is much higher than in other sand seas, ranging from ~280 mm in the west to nearly 400 mm in the east. Thus, this sand sea was not even listed as a notable desert in the authoritative book on Chinese deserts (Zhu et al., 1980). However, this desert is ~400 km long from east to west and covers an area of ~16,000 km^2. This sand sea is probably one of the best illustrations of the importance of fluvial processes in creating sand seas, as the sand sea consists mainly of dunes overlying the flood plain and terraces of the Yellow River. In

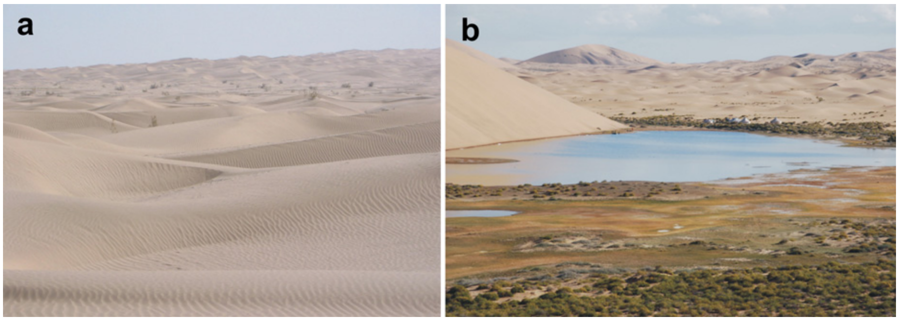

Fig. 3. Sand seas in northwestern China: The mobile dunes [front ones (secondary dunes on the surface of a compound longitudinal dune) are just ca. 3 m high, but the large dunes in the photo are a compound longitudinal dune striking NE (right)–SW (left), ca. 50 m in height] in the central Taklamakan (a) and an inter-dune lake (the dunes are compound, ca. 150 m high from the lake surface to the peak in the far distance of the left part) in the southeastern Badain Jaran (b).

the flood plain, the dunes are mostly barchans some 3 m in height. In the first (lowest) terrace the dunes may reach a height of 20–25 m, while the highest dunes of this sand sea are compound dune chains which can reach a height of 50–60 m, occurring mainly in the transitional zone between second and third (highest) terraces. This shows that some of the dunes were formed when the terrace risers became covered by aeolian sand. On the third terrace the dunes are relatively low, normally less than 3 m in height. Over 60% of the dunes are active. Almost everywhere, geomorphological hazards arising from dune migration and encroachment occur in the southern margins of the sand seas in China, except in Kubuqi where northward transportation of the aeolian sand has been a permanent threat to the irrigated farmlands on the southern bank of the Yellow River.

2.2. *Fields of stable dunes (past sand seas)*

There are five large sandy lands that consist mainly of stabilized dunes in northern China. Gurbantunggut is the only one located in the west, with the other four in the east (Fig. 1). The major sandy lands are Maowusu (Mu Us) in the southern Ordos Plateau, Hunshandake (Otindag) in eastern Inner Mongolia, Horqin in the western Northeast Plain, and Hulunbeier (Hulun Buir) in the Hulunbeier Plain (Fig. 1). Although there is historical literature recording aeolian sand activities in the sandy lands, many of the active dunes are due to more recent individual re-activation triggered by human activities (Hou, 1973; Zhu and Chen, 1994). The total area of each sandy land is not small (Table 1), but the coverage of dunes is relatively low, particularly in Hulunbeier Sandy Land where only three sand dune belts occur (Fig. 4a). More than two thirds of the Hulunbeier is covered by fluvial and lacustrine sediments but without the occurrence of aeolian sands. Vegetation cover may reach up to 50% on dune surfaces. The sandy lands have been used for animal grazing and agricultural cultivation for generations with a low degree of re-activation earlier, and there are permanent residential sites in their interiors.

The Gurbantunggut Desert in the Zhungar Basin has been described as the second largest desert in China (Fig. 1 and Table 1) in almost all literature relating to Chinese deserts (e.g., Zhu et al., 1980; Yang et al., 2004). However, there is an obvious controversy in the description of this desert, because its character suggests a sandy land according to Chinese classifications. Most of the dunes are stabilized by plants including *Haloxylon*, *Ephedra*, *Artemisia* and *Carex*, showing linear forms and being 10–50 m in height. Besides, about two thirds of the Gurbantunggut is desert steppe and gravel desert (Gobi), not covered by dunes. In response to the eastward decrease of precipitation, the landscape changes from desert steppe over stable dunes to barren Gobi from west to east. In the northwestern part of this desert, erosional landforms, namely yardangs, are common. In recent decades human activities have accelerated the re-activation of some of the stable dunes in this desert, particularly in its southern margins, although it seems that active dunes have been reported from this desert over the past several hundred years (Zhu and Chen, 1994; Zhu, 1999; Yang et al., 2004). The widely scattered ceramics of the Tang Dynasty (618–907 AD) in the southern margin suggest that the environment was more suitable for agriculture at that time, since this 1 km wide southern margin is now severely desertified (Zhu et al., 1980).

The Maowusu Sandy Land is bordered by the Kubuqi Sand Sea to the north, the Yellow River to the east and west, and the Loess Plateau to the south. The sedimentary sequences in the transitional zone between this sandy land and the Loess Plateau are therefore indicative of changes in the extent of the desert. The dunes in this sandy land, often barchan chains, may reach a maximum height of 20 m, and some of them were formed by aeolian sands covering the earlier loess hills. Flood plains along river courses, and inter-dune wetlands, are common in this dune field. While *Artemisia* grows on the dunes, *Salix* and *Hippophae* are common in the inter-dune lowlands. In this dune field there are ~170 saline and fresh water lakes of various sizes (Zhu et al., 1980). Several rivers with headwaters in this sandy land are able to flow across the area and into the Yellow River.

Bordered by flat grassland to the north and mountainous loess landscape to the south, the Hunshandake Sandy Land is ~21,400 km^2 in area and is relatively well vegetated. In addition to shrubs such as *Artemisia* and *Salix*, there are also some trees, such as *Ulmus*, *Malus* and *Pinus*, growing in the dune field (Fig. 4b). The dunes, ranging in height from a few metres to 30 m, are barchans, parabolic, linear and grid-formed types, relating to various patterns of the region's surface wind systems. In general, the inter-dune areas are extensive, flat and well vegetated, sometimes even with an extensive area of wetlands (Yang et al., 2007a).

With an area of 42,300 km^2, the Horqin (Keerqin) Sandy Land is the largest dune field in the semi-arid regions of China. This dune field consists of various mosaics of wetlands, agricultural areas, stabilized (probably since mid-Holocene), semi-stabilized and active aeolian sands; but the stabilized dunes are predominant. The dunes occur mainly on fluvial plains along river courses, on alluvial fans of mountainous forelands, and on shoreline areas of lakes. They are often typical source-bordering dunes (Zhu et al., 1980), generally below 10 m in height with a maximum of 30 m. Principal types of dunes are sand sheet, sand ridge, barchan, barchanoid chain, honeycomb-shaped and lunette dunes. For the formation of this dune field, aeolian and fluvial processes are evaluated as being of equal importance, as the lateral migration of channels has prepared space and sediments for the dunes (Han et al., 2007). Due to high mean annual rainfall (300–450 mm), this dune field possesses the best moisture condition of all dune fields in China. The natural vegetation may have been forest in many parts of the dune field prior to intensified human occupation several centuries

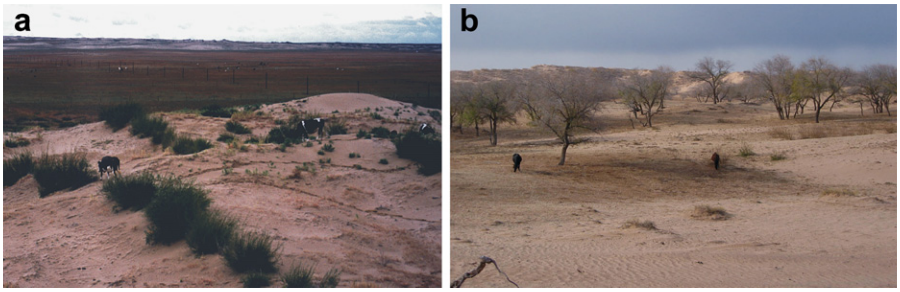

Fig. 4. Dunefields in the eastern part of the Asian middle-latitude deserts: Isolated dunes (a simple sand belt, ca. 10 m in height) in the Hulunbeier (a) and trees growing in the dunes (linear form, ca. 20 m in height) of Hunshandake (b).

ago (Zhu et al., 1980). However, this sandy land has been used for agricultural cultivation and animal grazing for generations, and it is a typical transitional zone between grain production and animal husbandry, and a classical case of the controversy associated with human-induced desertification (Zhu et al., 1988). Nevertheless, the present occurrence of the mobile sands is attributed largely to degradation of vegetation in relation to human activities such as farming and grazing.

3. Key factors controlling the occurrences of sand seas in northern China

About 45% of the arid and semi-arid regions of China is covered by active and stable dunes (Zhu et al., 1980), with the drylands of China having the highest percentage of dune landforms on Earth. In contrast, aeolian sand covers less than one percent of the arid zone in the Americas (Lancaster, 1995), while active sand dunes occupy between 15% and 30% of the arid areas in the Sahara, Arabian Peninsula, Australia and Southern Africa (Goudie, 2002). In this sense, the dryland dune fields of China must be associated with special geo-environmental conditions. Whilst most of the dunes in China are depositional landforms created directly by aeolian processes, two other components, namely sediment supply and availability, are crucial to the development of the dunes (Kocurek and Lancaster, 1999).

3.1. Climate

Isolated dunes can occur in many different environments, such as shoreline areas of lakes and coastal regions in all kinds of climate zones. But sand seas and large dune fields, as widely accepted, are generally associated with arid and semi-arid climates. Unlike arid climates caused by high-pressure systems in low latitudes, the drylands of China are due to remoteness from the oceanic moisture supply and the blockage of moisture pathways by high mountains and plateaus. With regard to the Taklamakan Sand Sea, the remote location and the mountainous blockage jointly cause a hyper-arid climate that is much drier than many other middle-latitude deserts in Asia. Early numerical simulation indicated that the dryness is even more due to topography than remoteness, as the establishment of the Siberian-Mongolian High was caused by uplifting of the Tibetan Plateau (Manabe and Terpstra, 1974).

Among all Chinese sand seas, only one (the Kubuqi) is located in an area where mean annual rainfall is >200 mm. Except Gurbantunggut all stabilized dune fields or sandy lands appear in regions with a mean annual precipitation between 200 mm and 400 mm, occasionally reaching 500 mm (Fig. 5). Mean annual temperature ranges between 6 °C and 12 °C in the sand seas and between −2 °C and 8 °C in the sandy lands of China. Although areas with lower temperature generally receive higher mean annual precipitation in the desert belt of northern China, the westward declining trend of mean annual precipitation must largely control the boundary between sand seas and sandy lands. Although the Gurbantunggut Desert occurs in the west, the higher annual rainfall there is due to moisture from westerlies. Sand seas do not necessarily occur in the areas with the least precipitation. This is true not only in northwestern China but also within a single desert. For example, average annual precipitation ranges between 24 mm and 47 mm in the Aksai Chin Plain in the western Tibetan Plateau, less than in any other desert. But there are no dunes in this area since it is covered by a cemented saline crust which impedes aeolian activity (Miehe et al., 2002).

Wasson and Hyde (1983) claimed that wind strength is not important in differentiating desert dune types. This appears to be relevant to the distribution of sand seas in northern China also. Referring to methods summarizing the nature of wind, sand drift potential (DP) and resultant drift potential (RDP) in the sense of Fryberger and Dean (1979) are often used in aeolian geomorphology (Bullard, 1997). However, only the mean annual wind velocity and the number of days with strong winds are considered here, in order to easily reveal large-scale differences and similarities. Both mean annual wind velocity (Fig. 6) and number of days with strong winds (speed reaching 17 m s^{-1}, Fig. 7) are lower in the areas of the sand seas than in sandy lands. The lowest values of these two indicators occur in the largest sand sea, the Taklamakan, probably due to blockage of the airflow by the surrounding mountains. The transport capacity of the wind is important to the building of the dunes (Kocurek and Lancaster, 1999), but differences in wind strength appear not to be relevant to the distribution of the sand seas in northern China. For instance, the Taklamakan, the largest sand sea of China, is located in a low-wind energy environment, whereas the Hunshandake, the field mainly with stabilized dunes at present, experiences amongst the strongest winds of China's deserts. In other words, neither the extension of the sand

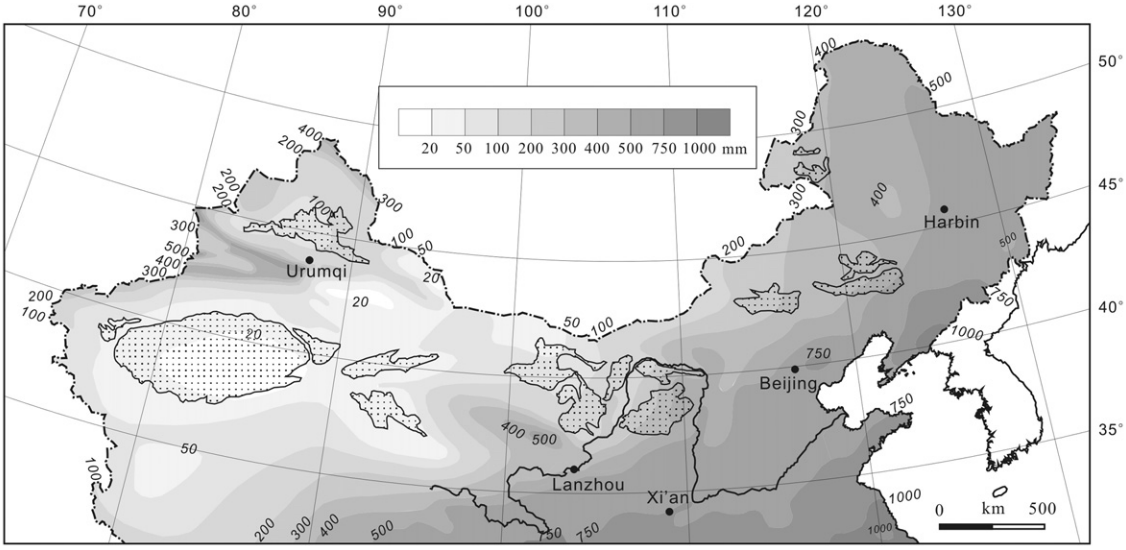

Fig. 5. Mean annual precipitation in northern China (Modified from China Meteorological Administration, 1994).

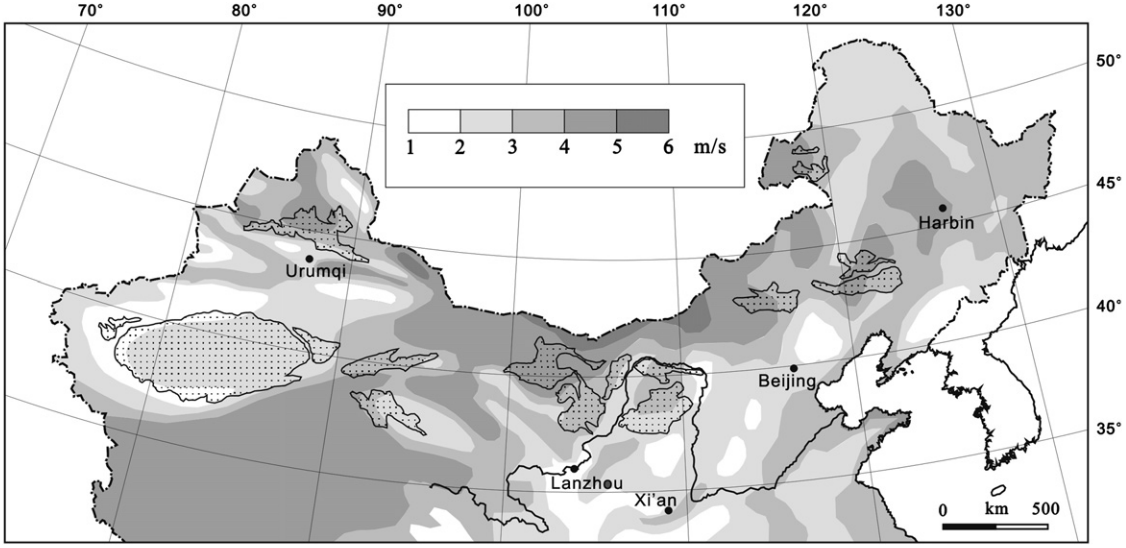

Fig. 6. Mean annual wind velocity in northern China (modified from China Meteorological Administration, 1994).

seas nor the height of the dunes shows an obvious relationship with wind strength.

3.2. Regional tectonics

Sand seas occur in the two higher levels into which the Chinese landmass is divided, while the fields of stabilized dunes are mainly in the lower altitudes. The occurrence of sand seas in northern China appears not to be associated with large-scale tectonics, but more to regional-scale structures, namely endorheic basins or forelands of mountain ranges, where rivers with headwaters in the surrounding mountains flow into or past the sand sea. The tectonic framework of China was established during the Mesozoic Era, with the final formation of the various basins in northern China being associated with tectonic movements mainly since the Pliocene (Ren, 1980).

Large quantities of loose sediments have accumulated over time in the floors of the dryland basins, providing sources of sand for later aeolian reworking. The sediments are often brought into the areas of the present sand seas directly by fluvial and alluvial processes from the mountains, but they may have already been broken into sand-sized particles in their original locations in the mountains by glacial processes or frost weathering (Yang, 1991). Particularly in the case of Taklamakan, all mountains around it are sufficiently high for glaciers in the present interglacial, and the large relief energy enables abundant fresh sediments to be transported into the sand seas. Unconsolidated sediments (mainly alluvial and fluvial) are generally 500–600 m thick beneath the dune landscape, but may exceed 900 m in the southern margin of the sand sea (Li and Zhao, 1964). The thickness of loose sediments is much less in the Badain Jaran than in the Taklamakan, probably due to the greater remoteness of the mountains. Nevertheless, sediments from mountains in various directions, particularly from those located to the south, are brought to the margins of the Badain Jaran by alluvial and fluvial processes. In the Taklamakan and in the Badain Jaran, the highest dunes occur in the forelands of the mountains which also act as barriers to wind flow (Zhu et al., 1980; Yang, 1991). Detailed knowledge about the relationship between any sand sea and its

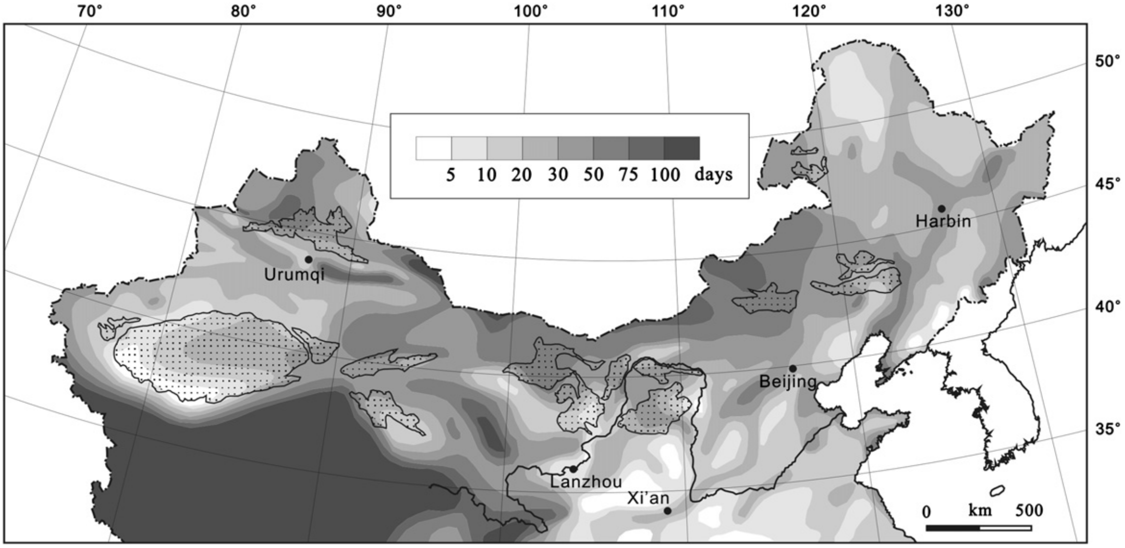

Fig. 7. Mean annual number of days experiencing strong winds (instant velocity reaching 17 m s^{-1}, modified from China Meteorological Administration, 1994).

main incoming rivers or streams is, however, not yet available so far, and should be a key aim for the future research.

3.3. *Sand sources*

Although the tectonic structure of the endorheic basins can easily lead to the opinion that the sand of each sand sea has its own source areas in northern China, it is still of importance to clarify whether dune sands have been transported from one sand sea to another. Sedimentological features of the sands suggest that the sand is principally different from sand sea to sand sea. In terms of grain size, the sands of dune crests from the Taklamakan have on average a mean grain size of 0.136 mm (2.88 Φ), 0.179 mm (2.48 Φ) for the sands from the Badain Jaran, and 0.189 mm (2.40 Φ) from the Hunshandake Sandy Land (Yang, 1991; Li and Yang, 2004).

Mineralogical differences among the sand seas also occur in the heavy mineral assemblages of the sand, the content of calcium carbonate, and micro-texture on the quartz grains. For the measurements of heavy minerals (density >2.9 g cm^{-3}), only the results for the sands of grain size fraction 0.01–0.25 mm are used, because no comparable data are available from other grain size fractions. Taking the Taklamakan and Badain Jaran for comparison (Fig. 8), the content of heavy minerals in the Taklamakan is much higher than in the Badain Jaran. It ranges between 6.7% and 17.5% in the Taklamakan, whereas in the Badain Jaran the sample with maximum value contains only 3.4% of heavy minerals. Besides, the assemblages of heavy minerals are different in these two large sand seas. Unstable minerals amount to over 40% of all heavy minerals in the Taklamakan, whereas they account for less than 26% in the Badain Jaran (Yang, 1991). Imprints of glacial processes can be relatively easily found in the micro-texture of quartz grains in sands from the Taklamakan, but not in the sands from other sand seas in northern China (Yang, 1991). The difference in the content of calcium carbonate is obvious as well. The percentage of calcium carbonate varies between 5% and 13% in the dune sands of the Taklamakan (Wang, 2007), but is generally <2% in the Badain Jaran (Li and Yang, 2004). The percentage of calcium carbonate is <0.5% in all samples taken from the Hunshandake (Li and Yang, 2004).

On the one hand, sedimentological parameters such as grain size, heavy mineral assemblages and calcium carbonate content reveal the fundamental nature of the sands of the sand seas. On the other hand, these indicators are strongly associated with onsite climate conditions and they can alter during weathering processes in a long term. Therefore, geochemical approaches (e.g., Arbogast and Muhs, 2000; Muhs, 2004) have been applied increasingly to study the sources of aeolian sands in northern China, particularly during the last decade.

According to neodymium and strontium isotopes data (Chen et al., 2007), desert sands in China can be divided into three groups or source regions. The Gurbantunggut, Hunshandake, Hulunbeier and Korqin belong to the same group. The Taklamakan, Badain Jaran, Tengger and the dunes in the Chaidam are similar in their neodymium and strontium isotopes. The third group includes only the Kubuqi and Maowusu. Neither surface wind patterns nor geographical locations could support the idea that the sands of the four sandy lands crossing the entire desert belt from west to east could be from the same provenance. However, it might be a reasonable analog if the mountains near these four regions were from the same orogenesis. It could be assumed that a large portion of the sediments in the Taklamakan, Badain Jaran and Tengger are sourced from different parts of the Tibetan Plateau, by rivers with their headwaters on the plateau and flowing to the sand seas. If neodymium and strontium isotope values are homogeneous in the rocks of the Tibetan Plateau, these isotope values would be helpful for inferring the ultra-origins of the aeolian sands. But the U–Pb ages of the detrital zircons from the sand samples show significant differences between Hunshandake and Korqin, as there are more Cretaceous zircons in Korqin while the sediment of Hunshandake has a high portion of zircons originating from rocks of the age around Devonian-Carboniferous boundary (Stevens et al., 2010). Therefore it is unlikely that the sand of Hunshandake and Korqin can share a same source although neodymium and strontium isotopes data of the sands from both sandy lands are similar.

Measuring $\delta^{18}O$ in quartz is a potentially useful approach to trace the provenances of desert sand, because the $\delta^{18}O$ value in quartz remains unchanged during Earth surface processes

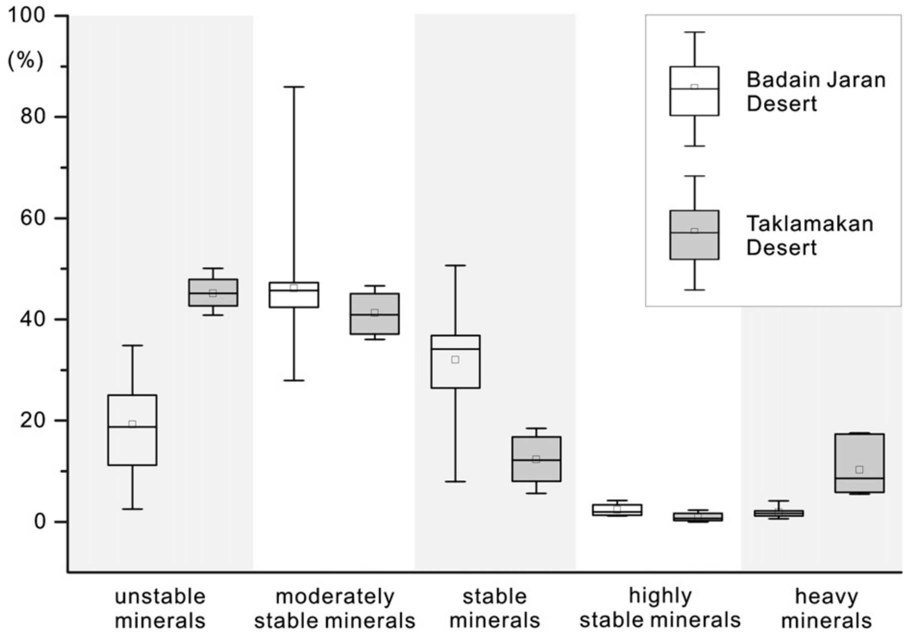

Fig. 8. Mean percentage of heavy minerals in the Taklamakan and the Badain Jaran and the relative abundance of various groups of heavy minerals in each sand sea (the square in the middle of the box represents the mean value, and the range, lower quartile, upper quartile and median are all marked respectively. Original data from Yang, 1991).

including diagenesis and alteration if no recrystallization takes places (Clayton et al., 1978). Oxygen isotope data relating to the composition of quartz sands are available for Taklamakan, Badain Jaran, Hulunbeier and Hunshandake (Yang et al., 2008a). Typical fractions of grain size for each region were selected for analysis and the results showed that the sands of these four regions are not the same, with the highest value for the Taklamakan and the lowest for Hunshandake (Fig. 9). Therefore, the oxygen isotopes of the quartz sands indicate different origins of sand for each desert. The rare earth elements (REE) data reveal not only differences among various deserts but also regional inconsistencies within a sand sea and differences between various grain size fractions from the same sand sample. The REE (La, Ce, Pr, Nd, Pm, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu and Y were measured using ICP-MS) concentrations and patterns show differences among Taklamakan, Badain Jaran and Hunshandake (Yang et al., 2007b,c). Based on the REE features, it was suggested that coarse sands are different from area to area within the Taklamakan but the fine sand is more homogeneous (Yang et al., 2007c). The Taklamakan can be divided into several catchments, each receiving fluvial sediments from a specific river. In this sense the coarse sands could be different from catchment to catchment. The directions of dune movements, interpreted from dune morphology, also suggest that the sands are not intensively mixed during transportation as the dunes move forward parallel to one another (Zhu et al., 1981).

As stated above, inconsistencies occur among various geochemical indicators, and geomorphological context is essential for interpreting geochemical data. The radiogenic neodymium and strontium isotopes, REE and oxygen isotopes have all shown some potential in identifying the provenances of the sand, but each seems to have its own limitations; although, theoretically, the latter indicators, compared to mineralogy, could not be readily altered by surficial processes such as weathering and transportation.

4. Key factors responsible for the late Quaternary changes of the sand seas

The sand seas in western China currently receive little moisture from the southeastern monsoon. Remains of lacustrine sediments, however, occur in the various parts of the Taklamakan, confirming the occurrence of late Quaternary wetter periods in the sand sea, caused probably by changes in westerly strength (Yang et al., 2006; Yang and Scuderi, 2010). The sandy lands in eastern China are sensitive indicators of shifts in the regional moisture balance associated with changes of the East Asian monsoon systems. The differences in moisture sources probably account for the different responses between deserts in western and eastern China during the Last Glacial Maximum (LGM). During that period, some of the western Chinese sand seas experienced wetter conditions and, at the same time, the sandy land in eastern China experienced an activation of aeolian dunes (Jäkel and Zhu, 1991; Hövermann, 1998; Yang and Scuderi, 2010). Furthermore, in the palaeoclimatic community it is often understood that the intensity of the southeastern monsoons from the Pacific is crucial for moisture availability to the sand seas of northern China. However, based on modern meteorological data, several studies (e.g., Huang et al., 1998; Simmonds et al., 1999; Zhou and Yu, 2005; Zhou et al., 2010) show that there is a noticeable circulation in summer that brings abundant moisture from the Arabian Sea and the Bay of Bengal, passing through the Indochina Peninsula and the South China Sea, into mainland China. Zhou et al. (2010) further suggested that the Indian Ocean was the main moisture source of the East Asian summer monsoon. If the modern analog is applied to infer past changes, there is an urgent need to reinterpret the changes of sandy lands of China and their controlling factors. The role of the southwestern monsoon in influencing changes in the sand seas has not yet been clarified. The role of the wind intensities in the glacial activation of the dunes in these sandy lands is not yet well understood, either. Numerical simulations suggest an increase in glacial wind intensities on a global scale (Kutzbach et al., 1998), although there is little direct evidence from dune fields in the middle latitudes of North Hemisphere for this LGM increase (Muhs et al., 1996; Harrison et al., 2001; Yang and Scuderi, 2010). Future quantitative studies on the aeolian records in the sand seas would be able to answer the question of Quaternary wind intensity changes in these latitudes.

Many aeolian sequences in the sandy lands are characterized by intercalation of palaeosols which were formed under relatively

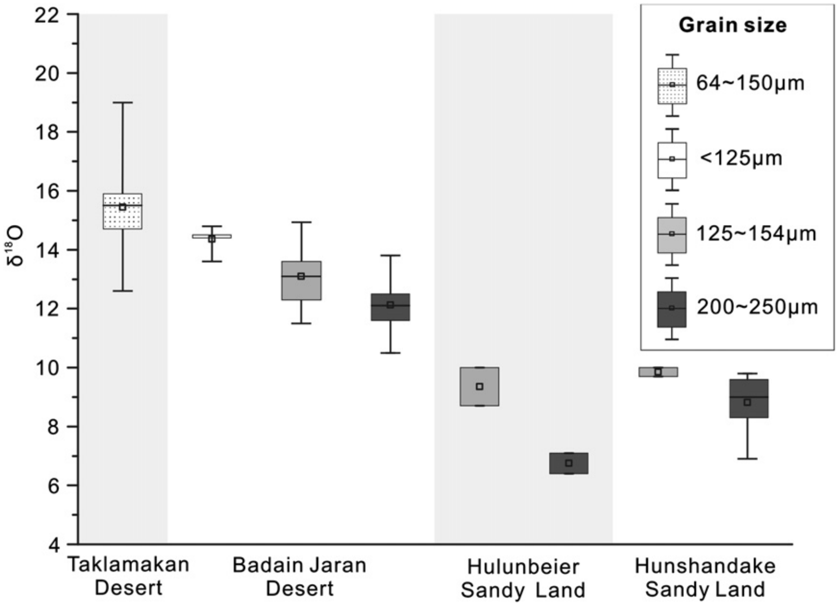

Fig. 9. Variations of the oxygen isotopes (per thousand) in the sands from various sand seas and stabilized dune fields (the square in the middle of the box represents the mean value, and the range, lower quartile, upper quartile and median are all marked respectively. Grain size indicates the fractions examined. Original data from Yang et al., 2008a).

good vegetation coverage. Generally speaking, these palaeosols were from the Holocene Climate Optimum, although the physical dating of various sequences could differ considerably. The duration of the Optimum has been suggested to be as short as just 2 ka (from ca. 5 ka to ca. 3 ka; Yang et al., 2008b) or as long as 7 ka (10 ka–3.6 ka; Li et al., 2002) in the Hunshandake. The onsite stratigraphical evidence of dune activities in Hunshandake, however, has not gone beyond the Last Glacial Maximum, because the sand of the LGM directly overlies bedrock (Yang et al., 2008b). Actually, very few chronological dates of aeolian sands from other sand seas fall into the period of the LGM, either. It is reasonable to deduce that the sandy lands were sand seas during the LGM, when the winter monsoon was strong due to an intensified winter monsoon caused by enlarged ice sheets in the Northern Hemisphere. Many of the OSL dates suggest that dunes in the sandy lands were still active during the early Holocene (11.7–8 ka, Mason et al., 2009).

Although the initial timing of the occurrence of the deserts in northwestern China is still a question for debate, it was probably no later than the beginning of the Quaternary according to several indicators including the increase in aeolian dust flux on the Chinese Loess Plateau (e.g., Alonso-Zarza et al., 2009). Sedimentological and geochemical indicators, however, suggest that the sand seas are still in an early stage of their development. For example, the grain size of the dune sand in the Taklamakan indicates that the sediment is enriched by fine fractions and therefore has not yet been fully reworked by wind (Besler, 1991). Also, micro-features on quartz grains still have footprints of earlier glacial and fluvial processes (Yang, 1991). The degree of weathering of the sediments in the Taklamakan is still in the early stages (Zhu and Yang, 2009), indicating that the sands are still fresh from their source rocks. More accurate ages of these sand seas need to be obtained by physical dating of the sands during future work.

5. Conclusions

The drylands of China are caused by their remoteness from oceanic moisture and the blockage of moisture pathways by high mountains and plateaus. The degree of aridity changes gradually on a large-scale, resulting in both arid and semi-arid climate zones at the same latitudes. The present geographical boundary between arid and semi-arid zones divides the landscape of sand seas in northern China into two distinct groups, namely modern sand seas with high dunes in the arid zones, and fields of stabilized dunes in the semi-arid zones, which were probably sand seas during the LGM. The various sand seas in northern China demonstrate great diversity in their extent, geomorphological setting, dune types, and climatic as well as hydrological backgrounds. The geographical distribution of the sand seas indicates that the endorheic basins are ideal for the development of sand seas, due to large amounts of loose sediments brought by rivers and streams with headwaters in the surrounding mountains. The Chinese sand seas suggest that sand sources mainly relating to fluvial and alluvial processes are more important than other factors in explaining their occurrence in these arid environments. Continuous inflows of fresh sediments probably account for the dune materials being relatively unweathered, as shown by sedimentological and geochemical indicators. On a large-scale, wind strength seems to have little influence on the occurrence of sand seas. In reflecting on the various studies of the sand sources of the sand seas in northern China, one has to keep in mind that geochemical data need to be interpreted within geomorphological contexts. Geomorphological settings and modern wind patterns as well as some geochemical indicators jointly support the opinion that the sands of the large sand seas are from local regions: that is, each sand sea has its individual provenance. It is unlikely that any of the sand seas were caused by incursions from another sand sea by aeolian processes.

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