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Spatial and temporal patterns of aeolian activities in the desert belt of northern China revealed by dune chronologies

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A B S T R A C T

As a part of the INQUA project "A Global Digital Database and Atlas of Quaternary Dune Field and Sand Seas", 337 age records from the desert dunes of China and 20 from Mongolian dune fields have been compiled in the database. This has opened the possibility of exploring and synthesizing the Quaternary environmental changes in the Asian mid-latitudes dune fields directly from the on-site aeolian sand archives. This paper assessed the sand dune chronologies in terms of geographical distribution, data quality and their implications for late Quaternary palaeoenvironmental reconstructions. The available ages are concentrated mainly in the last 20 ka and many are from the fields of stabilized dunes in the eastern portion of the desert belt in northern China. The number of records and the ratio between the records of stable state and the total records could act as a proxy for the palaeoenvironmental interpretation. The aeolian sand activities deciphered from the chronological data in the eastern portion of the desert belt in northern China show a reasonable correlation with the general global climatic curves at the glacial–interglacial timescales. The limited aeolian sand records from the glacial period, however, hamper the understanding of the detailed features (e.g., forms and processes) of the dune fields during glacial times. In the last two millennia, however, there has not been any meaningful correlation between aeolian dune activity and climatic variation at the centennial time scales, probably due to the complexity of the aeolian sand systems and human interventions. Extending the coverage of dune chronology both temporally and spatially is urgently needed for a full understanding of the environmental changes in the dune fields.

1. Introduction

As a common landform, windblown sand covers approximately 6% of the land surface area on Earth (Pye and Tsoar, 2009) and remains an important palaeo-environmental archive of the Quaternary (Goudie, 2002; Thomas, 2011; Lancaster et al., 2013; Warren, 2013; Williams, 2014). In China, ~566,000 km^2 of land are occupied by sand dunes, which are probably the most extensive Quaternary deposits of China. In much of the arid zone in China, sand seas are the most readily available recorder of the past climate changes. Located in the eastern part of the middle latitude Asian desert belt, the sand seas in China span the transitional zone between north-hemispheric westerlies and the East Asian Monsoon system, marked by a greater climatic variability (e.g. Tian et al., 2013). Sand seas play a unique role in palaeo-climate reconstruction in arid China.

Exploration of the palaeo-environmental information preserved in the dunes, however, has long been hampered by the problem of dating. Other factors, such as the complexity of interpreting the discontinuous sediment sequence in sand seas, lack of palaeoclimatic proxies, and lower accessibility of sand seas, imposed further difficulties on palaeo-environmental studies. Therefore, early records regarding the past climate changes in deserts of China were mainly obtained from the loess deposits adjacent to the sand seas (e.g., Zhu et al., 1981). Lacustrine sediments in the desert also provided valuable information about past climate changes in arid China (Pachur et al., 1995; Liu et al., 2002; Herzschuh et al., 2004; Chen et al., 2008; An et al., 2013). Nevertheless, it is hard to derive the processes and mechanisms of the sand seas' responses to the climatic variations from those indirect archives. With the development of luminescence dating, many records with physical dating from the sand seas have emerged, especially in the past decade. The rising amount of the records allows us to eliminate the

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assumed correlation between loess or lacustrine records and dune activity, and capture sand seas' true response to climate changes. Up to now, over 300 records from China and Mongolia have been compiled in the database for the INQUA Atlas of Quaternary Dune Activity. These ages were mainly derived from peer-reviewed publications (Hofmann and Geyh, 1998; Li et al., 2002; Yang et al., 2003; Yang, 2004; Lu et al., 2005; Yang, 2006; Yang et al., 2006; Yang et al., 2008; Zhou et al., 2008; Mason et al., 2009; Hülle, 2011; Li and Fan, 2011; Pötsch, 2011; Zhang et al., 2011; Stauch et al., 2012; Yang L. et al., 2012; Zhao et al., 2012; Zhou et al., 2012; Yang et al., 2013). In this paper, we first describe briefly the environment of the sand seas in China, followed by introducing the database with the regard to deposition states, spatio-temporal coverage, sampling methods and quality of the records. As the dune fields in Mongolia belong to the Asian middle-latitude desert belt as well and can often be seen as part of the Gobi Desert whose larger portion is the middle part of the desert belt in northern China, we also pay attention to the available chronological data obtained from the dune fields in Mongolia. Finally, environmental changes of the sand seas in China and Mongolia are interpreted based on these chronologies.

2. General settings of the dune fields in northern China

A total of 12 large sand seas are scattered roughly between 36 and 50° N in north China, forming a wide and long desert belt in the middle latitudes (Fig. 1). Under the impact of the East Asian Monsoon system, the dune fields situated to the east of 107° E consist mainly of inactive dunes. Active dunes occupy the western sand seas with the exception of the Gurbantunggut Desert, which has a mean annual precipitation of ca. 200 mm, and most of the dunes there are fixed by vegetation at the present time. Endorheic basins or forelands of mountain ranges are the preferred locations for the development of dune fields in China due to the availability of large amounts of loose sediments brought by the steams with headwaters in the surrounding mountains (Yang X. et al., 2012). In contrast to the widespread sand seas in China, dunes in Mongolia are rare, and only <20,000 km^2 land is covered by the sand dunes which occur mainly in the northwest part (Ikh Nuuruud Basin) of Mongolia (Yang et al., 2004). In addition to the scarcity of precipitation, the dune fields in China and Mongolia are characterized by a cold winter climate. Due to the influence of the strong Siberian–Mongolian anticyclone, the mean temperature of January ranges from −10 °C in the Taklamakan Desert to −25 °C in Hulunbeier Sandy Land (Fig. 1), and in Mongolia it drops below −30 °C. The cold winter generates a 3–6 months frozen season, during which some of the dune sand can be fixed by pore ice especially in the wetter east. In April 2012, we observed frozen sand below the depth of 1 m in Hunshandake (Fig. 1). The sand seas in the western portion of the Chinese desert belt are characterized by the occurrence of giant dunes. In the southeast part of the Badain Jaran Desert are the highest dunes (460 m) on Earth (Yang et al., 2011a). In the Taklamakan Desert, the largest sand sea in China, over 80% of dunes are higher than 50 m (Zhu et al., 1980).

3. Deposition state

Spanning several climatic zones, the dune fields in China and Mongolia incorporate a variety of landscapes at present. It is, therefore, reasonable to envisage diverse depositional environments in the past. From the perspective of stratigraphy, all those depositional environments are categorized into two deposition states, i.e. accumulating and stable. In this database, aeolian sand is the only deposit considered as in the accumulating state, while the category of stable state includes paleosols, (sandy) loess, lacustrine sediments interbedded with aeolian sand, calcareous layers and cemented plant roots. The paleosols, occurring widely in the eastern dune fields, are strong evidence for limited aeolian activity. The net sedimentation rate of paleosols is very low, only 1/3–1/10 of the aeolian sand in Hunshandake (Yang et al., 2013). The paleosols have a much higher total organic carbon (TOC) than aeolian sand. In eastern China's dune fields, the Holocene paleosols are much darker than the A horizons of present soils, indicating a much denser vegetation coverage than that in presently fixed dunes. The (sandy) loess deposits interbedded within aeolian sand are found in the fringe of the middle and western dune fields, and they are always treated as a signal of aeolian abatement. In the interior of western sand seas, the evidence of environmental changes is rare due to the hyper-arid climate. However, lacustrine deposits scattered in some dune fields imply high lake levels (Yang and

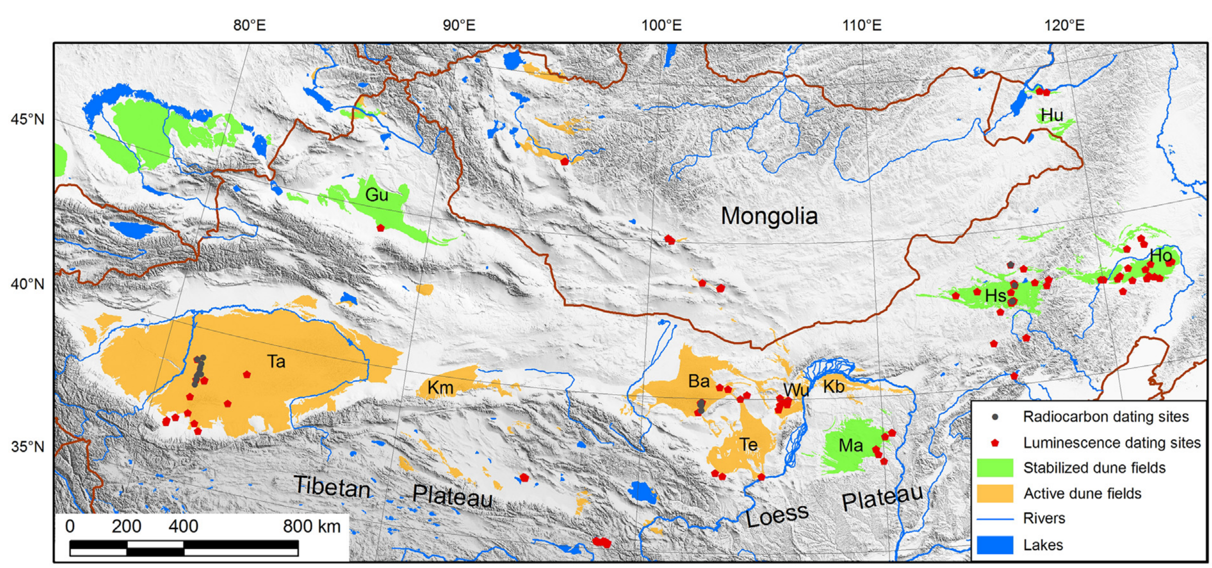

Fig. 1. Location of sand seas and dating sites in China and Mongolia. Hu, Hulunbeier; Ho, Horqin; Hs, Hunshandake; Ma, Maowusu; Gu, Gurbantunggut; Ta, Taklamakan; Km, Kumtag; Ba, Badain Jaran; Te, Tengger; Wu, Wulanbuhe; Kb, Kubuqi.

Scuderi, 2010) or even a unified lake in the past (Zhao et al., 2012). In the Badain Jaran and Tengger, there are also cemented plant roots, always occurring not far from the lakes or lacustrine deposits (Yang et al., 2003), indicating wetter conditions. The hard calcareous layers interbedded with in aeolian sand deposits in the Badain Jaran (Yang et al., 2003) suggest limited aeolian activity of the dunes.

4. Spatial and temporal distribution of the records

By October 2013, there were 337 published age records of aeolian sand dunes from north China and 20 from Mongolia in the INQUA Global Digital Database of Quaternary Dune Field and Sand Seas: 331 of them were luminescence ages, and the remaining 26 records were dated by radiocarbon. Considering the extensive distribution of dune fields in north China, these chronologies are far from satisfactory for a thorough understanding of palaeoclimatology and Quaternary environmental changes. The unevenness of geographical allocations of the chronological sites can be easily seen in Fig. 1 and Table 1. Although the age data cover the eastern portion of the desert belt in northern China relatively well (Hunshandake and Horqin, for instance), others, especially dune fields in the arid western regions, are less represented. To date, no single dune age of Kumtag has been reported (Fig. 1).

Table 1
Data distribution in dune fields for northern China and Mongolia.

Region	Luminescence			Radiocarbon	Total	Number of sites
	OSL	IRSL	TL			
Sand seas						
Taklamakan	20			14	34	22
Badain Jaran			19	8	27	16
Wulanbuhe	18	1			19	6
Tengger	14				14	4
Tibetan Plateau	21	32			53	23
Mongolia		20			20	8
Sandy land						
Hunshandake	59	3		4	66	20
Horqin	70				70	21
Maowusu	26				26	6
Gurbantunggut	15				15	3
Hulunbeier	6				6	2
Others	3	4			7	4
Total	252	60	19	26	357	135

In the Hulunbeier, six age records (Li et al., 2002, records CHNL00156-161) from 2 sites are included in the database. Located in the northernmost part of China, Hulunbeier is characterized by a wetter and colder climate. There are only three sand dune belts in this dune field (Yang X. et al., 2012). Most of the dunes are well-vegetated by grass, shrubs, and even trees (e.g. *Pinus sylvestris var. mongolica* and *Ulmus pumila*) (Zhu et al., 1980). Due to strong wind erosion, blowouts occur widely in this area. Both of the sections are the residues of the former dunes.

Horqin is also characterized by stabilized dunes whose height is generally less than 10 m (Yang X. et al., 2012). The rivers with headwaters in the mountains in the west flow through the dune field and bring large quantities of the sediments. Owning to the wetter climate conditions, farmland is widespread, especially in the inter-dune areas. Nearly half of the records (records CHNL00042-53, CHNL00069-73, CHNL00086, CHNL00088-98) are obtained from the inter dune areas (sand sheets), and arable soil develops in the upper parts of some sections.

Located in the eastern portion of the dune belt, Hunshandake is characterized by stronger wind energy than other sandy lands of China (Yang X. et al., 2012). Parabolic dunes and compound parabolic dunes are the dominant type in this dune field, and produced 40 out of 66 of the ages. Although it has the second largest number of records among all dune fields in China, unevenness of spatial distribution is still remarkable, as only a small fraction (14 out of 66) of age records (Yang et al., 2013, records CHNL00189-202) are obtained from western Hunshandake. This is in a large part due to the accessibility, because many of records are along main roads in the east.

Located to the north of Loess Plateau, Maowusu (Mu Us) used to be regarded as a major source of the loess deposits (Liu, 1985) and the palaeoenvironmental archives could be correlated with loess/palaeosol sequences in the Loess Plateau. All of the sampling sites are scattered in the east and southeast margin of the dune field, a transitional area where both loess and aeolian sand are found in the depositional sequence. In the sections of this area, loess layers were considered as the indicators of surface stabilization of dunes (Mason et al., 2009). The occurrence of loess deposits therefore is used as a proxy for dune stabilization in this database (records CHNL00099, CHNL00275 and CHNL00288).

Although dunes of Tengger Desert extend over 40,000 km^2, only a few dune ages have been reported (Table 1). All the records are concentrated in the southern rim of the dune field. Because of its adjacency to the Loess Plateau, some of the age records, like those of the Maowusu, are obtained from silt-dominated aeolian sediment sequences (records CHNL00330-331 and CHNL00317-319).

Wulanbuhe Desert consists of two main landform units. The higher east is dominated by bare mobile dunes. The west is thought to be a lacustrine plain overlain by the vegetated dunes (Zhu et al., 1980). All the records are distributed in the west, and most (CHNL00126-140) were obtained from the lacustrine sediments.

All the age records of Badain Jaran are from the eastern and southeastern margins of the sand sea. Badain Jaran is characterized by the occurrence of giant dunes and more than 100 inter-dune lakes in the southeast (Yang and Williams, 2003). Aeolian sands interbedded with lacustrine sediments often occur in the former shorelines of these lakes (Yang et al., 2004; Yang, 2006), recording aeolian activity variations in the past. Much of the research has been carried out in the shoreline areas of these interdune lakes.

According to the meteorological data, the Tibetan Plateau is the windiest area in China (Yang X. et al., 2012). There is a small area in the north of the plateau covered by aeolian sands, with elevations ranging from 2700 to 4600 m. Network and transverse forms are the dominant dune types in this high plateau. Most of the dunes are scattered around the Chaidamu (Qaidam) Basin, which was a mega-lake during MIS3 (Chen and Bowler, 1986; Hövermann and Süssenberger, 1986). The OSL records in this basin are concentrated in the linear dunes formed to the north of Chaerhan salt lake (records CHNL00170-188). Dunes in the plateau also occur in other intermountain basins, river valleys, and around lakes (records CHNL00223-256).

With an area of over 300,000 km^2, Taklamakan is the largest, but much less investigated sand sea in China. Various forms of dunes occur in this desert (Zhu et al., 1980). Most of the records were obtained from the areas along the Keriya River and along the southern margin of the sand sea, largely because of difficult accessibility to the interior parts (records CHNL00013-30, 168–169; CHNR00011-24).

Gurbantunggut is the only well-vegetated dune field in western China. The cold winter and thick snow help to keep the dunes in a stable state (Zhu et al., 1980). All the OSL samples are from the linear dunes in its southern margin (Li and Fan, 2011; records CHNL00257-271).

It is argued that dune fields in China experienced several times of expansion since as early as the beginning of the Quaternary, based on the particle size analysis of loess sediments in the south of

Maowusu Sandy Land (Liu, 2009). However, the records from dune fields are all dated to the late Quaternary, ranging from the last few decades to ~150 ka, and there are no older dunes or sand sheets reported. Most of the ages are quite young, and ~85% of the records are from the Holocene (Fig. 2), indicating probably the prevalence of reworking of aeolian sand. With decreasing age, the number of records increases rapidly except for the mid-Holocene, when there are fewer aeolian deposition records than those in the early Holocene. The relatively old ages are mainly obtained from active dune fields located in the western China (e.g. Badain Jaran), whereas most samples from the eastern portion of the desert belt are younger than LGM (Last Glacial Maximum) in age (Fig. 2). The occurrence of large dunes in western China may partially contribute to the preservation of older aeolian sediments. On the other hand, the high sedimentation rate and rapid reworking of sands would hamper the mega-dune's potential of capturing longer and continuous history of aeolian activity. Thermoluminescence dating of the highest dune (460 m) in Badain Jaran Desert showed that much part of the dune has been developed since 20 ka (Yang et al., 2003; record CHNL00031).

5. Sampling strategies and dating approaches

Over half of the records in the dune fields of China were obtained from artificial and natural sections. If unknown site types were excluded, sections provided ~86% of the age records. Section exposure makes the lithostratigraphic information of the dunes visible in the field and further affords assistance regarding sampling strategy and age interpretation. Recently, auger combined with the ground-penetrating radar (GPR) have also been applied in the chronological study of the dunes in China (Li and Fan, 2011, records CHNL00257-271). In the eastern stabilized dune fields, aeolian sand is better consolidated than in the active dune fields in the west due to the higher moisture content as well as the presence of vegetation and palaeosols. The free face of sections, therefore, could be held to 20 m in Hunshandake (Mason et al., 2009; record CHNL00119-123). In western China, there are fewer artificial exposures which could be utilized for sampling in the fields of active dunes. Also, the dry and unconsolidated sands raise a challenge for obtaining a deep dune profile. All these issues hindered exploring past aeolian activities over much longer timescales in the active dune fields in the western portion. One way to access palaeo-sand is sampling at the windward slope of the transverse dunes (records CHNL00017-19, 31–32), which included mega dune (Yang et al., 2003). This approach also worked to find Late Pleistocene sand in the Nebraska Sand Hills, although the dunes involved were very large (Mason et al., 2011). As yet, however, samples sampled in this way are younger than LGM (last glacial maximum). Another more widely used approach is dating aeolian sand which is interbedded with lacustrine (or fluvial) sediments (Yang et al., 2003, 2006; Yang, 2004, 2006; Hülle, 2011; Zhao et al., 2012). Owing to the protection of post-lacustrine cementation, aeolian sand is preserved in its original setting and could yield older ages such as 39.8 ka (record CHNL00013), 128.8 ka (record CHNL00150) and 151 ka (record CHNL00222) for the Taklamakan, Badain Jaran, and dune fields in Mongolia, respectively.

With respect to the dating types, OSL contributed to over three quarters of luminescence ages; followed by IRSL, which provided ~18% of the records. The remaining 19 luminescence samples from the Badain Jaran are dated by TL. Single Aliquot Regeneration (SAR) is the most common protocol employed in the luminescence dating, accounting for two thirds of the records. Two of the OSL

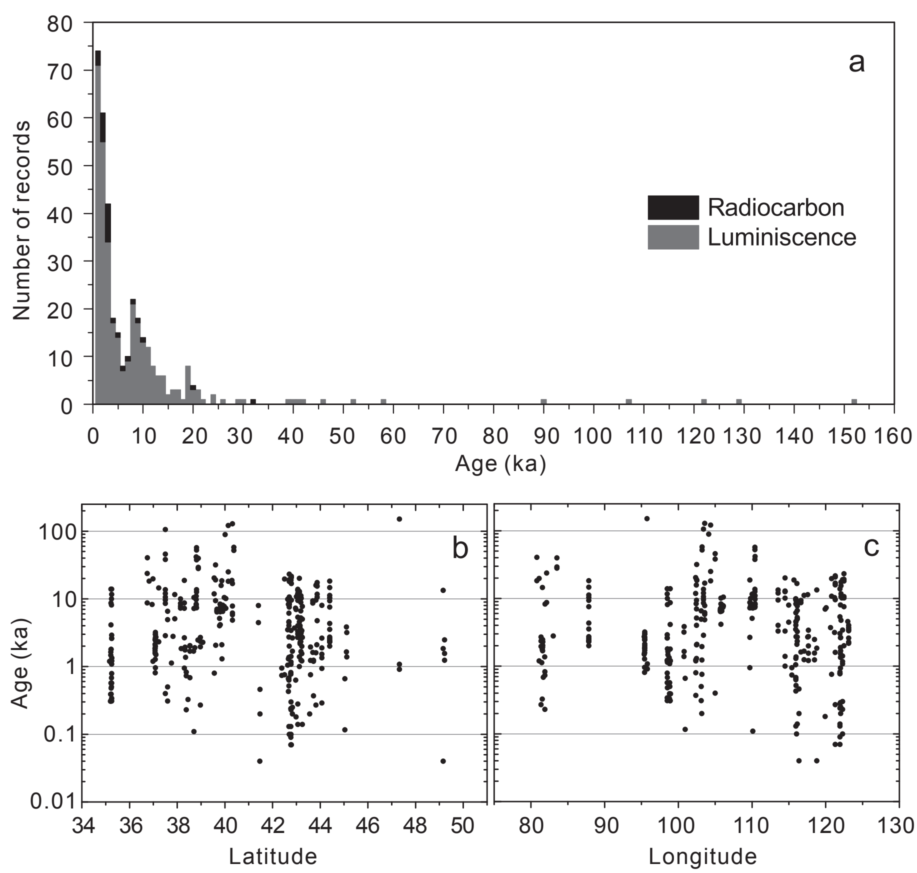

Fig. 2. Temporal (a, with a bin of 1000 years) and spatial (b and c) distribution of the total number of records.

ages were determined using a post-IR single aliquot regenerative protocol for the purpose of eliminating the influence from feldspar contamination (records CHNL00227-228).

Constructing the growth curve is a critical and always time consuming step during the SAR procedure. Standardized growth curve (SGC) procedure utilizes several samples to yield a general curve describing quartz growth character for a given sample (Roberts and Duller, 2004). The equivalent dose (D_e) for the sample, therefore, could be obtained by measuring the natural luminescence signal (L_n) and the response to a test dose (I_n). This procedure eliminates the regeneration stages for each aliquot and thus saves time. However, it turned out that there was not a globally but regionally based SGC for D_e determination (Telfer et al., 2008). In Horqin, the ages obtained by regional SGCs are in concordance with that based on SAR. The SGC/SAR ratios range from 0.83 to 1.13 with a mean value of 0.97 and show a positive relationship with D_e ($r = 0.56$, $p < 0.001$) (Yang L. et al., 2012).

Due to the sparse vegetation in the sand seas, only a few radiocarbon ages have been reported in northern China and Mongolia. In the wetter eastern part, palaeosols developed during the Holocene, on which radiocarbon dating was carried out (records CHNR00001-2, 25–26). Although vegetation in the western sand seas is quite limited, wood, dung and plant roots are well preserved in the ancient oases owning to the arid climate, providing materials for obtaining relatively accurate ages (records CHNR00011-24). The organic deposit in the lakes of the Badain Jaran was also used for dating (CHNR00008-10). In addition to the organic carbon, Yang et al. (2003) utilized cemented plant roots, which contained a high content of calcium carbonate, for the radiocarbon dating to determine the wet phase in the Badain Jaran (records CHNR00003-6). Most radiocarbon ages were obtained by the conventional method and only two records were dated using AMS.

6. Data quality

6.1. Luminescence

Although luminescence dating was applied in aeolian sand as early as the 1980s (Singhvi et al., 1982), very few luminescence ages had been reported in China until the introduction of SAR-OSL. According to the metadata of the database, 60% of the records in the database have the highest category rankings, implying the key information referring to the records is available. However, little knowledge is provided referring to data quality, e.g. precision and accuracy.

The main issue with relevance to the luminescence dating quality in the database is the age error bar. In desert environments, many factors would contribute to the error in the procedure of determining the equivalent dose (D_e) and estimating the dose rate (Wright et al., 2011; Wang and Wintle, 2012; Thomas and Burrough, 2016). The luminescence errors related to the samples in China and Mongolia increase with age, whereas the relative errors, with the mean value 8%, are independent of the D_e (Fig. 3a). As noted by Galbraith and Roberts (2012), the younger records (normally less than 1 ka) have higher relative errors although the absolute error is small (Fig. 3b). The errors mainly arise from the uncertainties of D_e. The young samples are also associated with thermal transfer, which would be a cause for the higher relative error (Wintle and Murray, 2006). Li et al. (2007) suggested that quartz had a lower precision in D_e determination than K-feldspar for the young samples in Horqin, northeast China. They ascribed the non-uniform D_e value for the quartz from young samples to the variable external dose rate that resulted from K-feldspar and zircon grains. That would be another reason for the higher relative errors.

In terms of accuracy, independent age control would be the best way to assess data quality. There are, however, few independent ages reported in association with the luminescence records in most cases. The data reliability, therefore, rely largely on the researchers' strategies for the luminescence dating and the suitability of the samples (Hülle et al., 2010; Hülle, 2011). For example, luminescence dating of the aeolian sand from the Tibetan Plateau shows that quartz-based OSL could underestimate the age by 29% relative to the K-feldspar IRSL for the same sample, and the discrepancy was attributed to the low luminescence intensities of the quartz fraction (Stauch et al., 2012). In such an instance, IRSL would produce a more accurate age, although it could also be expected to underestimate the true age due to anomalous fading. Some tests, e.g. recycling ratio test, recuperation test and dose recovery test, could evaluate the protocols applied in luminescence dating. Many of the referenced paper in the database do not give details about their data quality control measurements, and feldspar checking is the most reported test during OSL dating.

6.2. Radiocarbon

Despite the fact that the relative errors of the radiocarbon ages, with the mean value of 4.5%, are much smaller than that of OSL, we could not ensure that radiocarbon records are more reliable. Particular caution should be taken when interpreting the radiocarbon ages of the carbonate due to the hard-water effect (Yang et al., 2011b). Hofmann and Geyh (1998) reported that the radiocarbon age reservoir effect is ~3220 y for the inorganic fraction and ~1080 y for the organic fraction in the lacustrine sediments of the Badain Jaran Desert (Hofmann and Geyh, 1998). The reservoir effect is spatially and temporally specific (Hou et al., 2012), and thus developing robust correction models is challenging and critical for precise radiocarbon chronologies in the drylands. With respect to the radiocarbon ages of the palaeosols in the dune fields, uncertainties would arise from the disturbance of younger roots and reworking of the palaeosols during aeolian processes. The radiocarbon ages of palaeosols from Hunshandake are, however, in accordance with OSL ages (records CHNR00025-26), mirroring their credibility in dating the aeolian sands in this dune field.

7. Synthetic interpretation of the records

7.1. Problems with interpretation of the records

As a depositional landform, sand dunes are one of the most important palaeo-environmental archives and play a unique role in aeolian activity reconstruction. However, some caution should be paid before interpreting the age records (Telfer and Hesse, 2013).

Firstly, spatial heterogeneity is particularly common in the dune fields of northern China. Vegetation cover on a dune can be quite spatially variable, and the determination of the dune activity would largely depend on the position of sampling sections, especially in the case of the sandy lands in the eastern portion (Fig. 4). Isolated water ponds, quite common in Chinese sand seas, could also strongly affect the vegetation growth of the surrounding areas. In this regard, the information referring to the changes of water bodies, such as stream course variations should be excluded before discussing the palaeo-climatic changes. Both cautious pre-sampling field investigation and more data coverage are needed to overcome the problems caused by spatial heterogeneity.

Secondly, some palaeo-climatic signals would not be captured in the database due to sampling strategy and availability of datable materials. In this database, the stable state ages are defined as those obtained by dating the materials representing stable states as mentioned in section 3, i.e. paleosols, loess, lacustrine deposits,

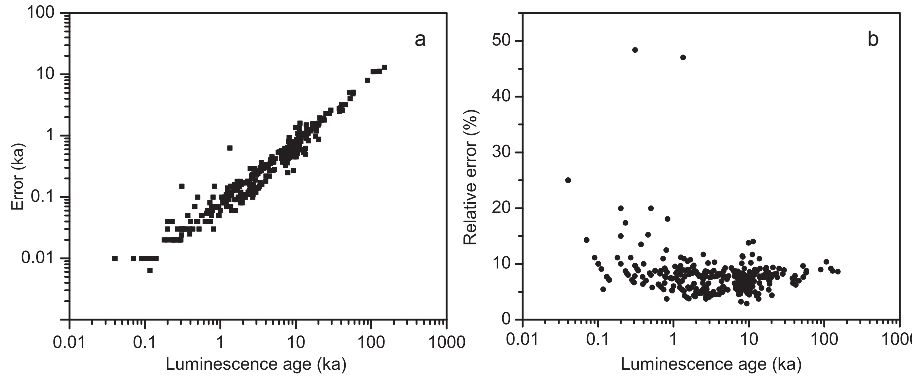

Fig. 3. Absolute (a) and relative errors (b) of the luminescence ages compiled for the Chinese and Mongolian dunes in the INQUA-initiated database.

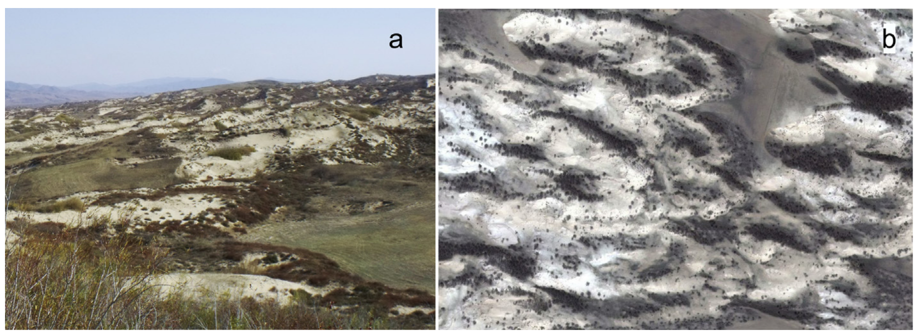

Fig. 4. Spatial heterogeneity of the vegetation coverage on the dunes in Hunshandake Sandy Land (a, field photography of the site around 43.16 N, 117.28 E; b, Google Earth Image of the site around 43.85 N, 116.73 E).

calcareous layers interbedded within aeolian sand, and cemented plant roots. However, there is some uncertainty in dating the "stable-state markers" and interpreting the stable state ages. Zeroing can be problematic when applying the OSL dating on lake deposits (Rhodes, 2011). Also, there can be three interpretations associated with OSL ages from paleosols (Mason et al., 2009; Lu et al., 2011), which could represent: 1) the age of deposition of aeolian sand before the dune stabilization when little deposition occurred during pedogenesis; 2) the age of deposition of sediment during pedogenesis; and 3) the age of bioturbation while the soil was at the surface. Therefore, many samples were obtained from the aeolian sand layers although these ages were used to decipher the ages of a stable state. For instance, Yang et al. (2006) reported a humid period occurred in the Taklamakan between 40,000 and 30,000 years ago. However, the ages were obtained by dating the aeolian sands which are interbedded in the lacustrine deposits (Fig. 5a), and, therefore, according to the metadata of the database, the aeolian sand indicate the accumulation state while the humid epoch could not be directly dated from its sediments. Similarly, many OSL ages in the sandy lands of the eastern portion are also obtained by dating the aeolian sand (Fig. 5b), and thus there is no direct stable state record in the database although two layers of palaeosol occurred in the section. As a result, the stable state was underestimated in previous studies. This would partially account for the decline in the amount of records from early and mid-Holocene (Fig. 2a).

Thirdly, it is challenging to explore the palaeoclimatic changes in the currently active dune fields of west China based on dune chronologies. Currently, the number of ages obtained from these active sand seas, which make up about 3/4 of the total dune field area, is fewer than that of eastern stabilized dune fields. Besides the difficult accessibility, the rarity of sediment layers indicating climate changes of the active dune fields, e.g. palaeosols, could account for the imbalance of the record availability. Due to the lack of paleoclimatic proxies in the active sand dunes, it is particularly difficult to extract information regarding climate changes from the dune chronologies. Also, without protection from these stabilized layers, the active sand dune tends to be more variable and have a short memory of paleoenvironment due to erosion/reworking. Although internal sediment stratigraphy can be a record of environment changes (e.g. Bristow et al., 2007), distinguishing local and regional signals would still be a challenge (Leighton et al., 2014), even without considering the difficulty of obtaining the stratigraphic information. In many cases, the variation in sand accumulation rate may be more promisingly obtained from the active dunes' chronologies. In the past decades, most of the research focused on exploring evidence of paleoclimate changes in the sand seas of China, while few studies have investigated dunes' internal stratigraphy and, combining the chronologies, implications for dune dynamics.

7.2. Interpretation of dune chronologies

Several reviews referring to the palaeoclimatic changes by synthesizing various records in the drylands of China have been published (e.g. Chen et al., 2008, 2010; Yang and Scuderi, 2010; Yang et al., 2011b; Scuderi et al., in press; Williams, 2014). However, much of the palaeo-environmental information is obtained from lacustrine sediments instead of aeolian sequences. This INQUA-initiated database provides a great opportunity to see the environmental changes of the dryland from aeolian sand archives. Palaeoenvironmental information of the sand seas could be derived from the deposition states, i.e. accumulating and stable, corresponding to drier and wetter environments, respectively.

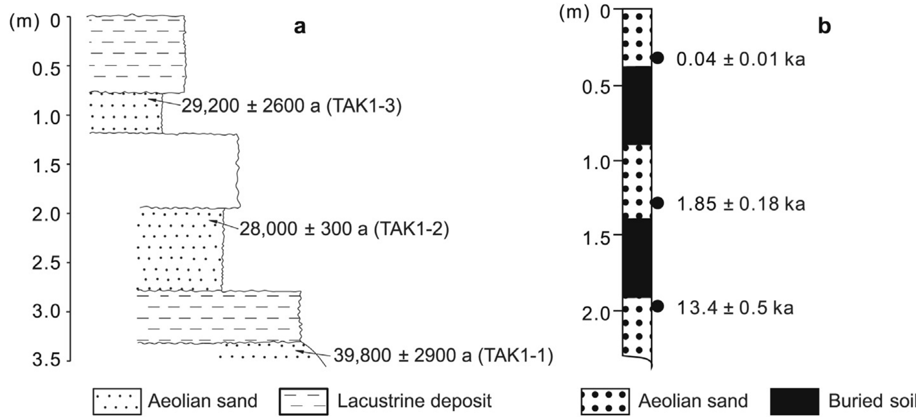

Fig. 5. Deposition records from Taklamakan (a, site at 38.89° N, 83.53° E, after Yang et al., 2006) and Hulunbeier (b, site at 49.16° N, 118.78° E, after Li et al., 2002).

Conversely, not all the drier periods are characterized by dune construction and dune destruction would occur during the late stage of the dry period because of sand starvation (Kocurek, 1998). Therefore, the absence of sand deposition could also provide palaeo-environmental information.

The database provides the first comprehensive analysis of aeolian activities up to ca. 150 ka directly on the basis of onsite aeolian records in China and Mongolia. The temporal distribution of the ages is highly uneven, as most of the ages are within the range of 1–10 ka. The records beyond the LGM are quite small in number, which makes it difficult to reconstruct high-resolution palaeo-climatic history on a glacial–interglacial time scale. However, the number of aeolian records in China exhibits a generally consistent relationship with the global climatic trends. There are no records of aeolian activities during roughly 60–80 ka (Fig. 6), probably due to the strong aeolian reworking during Marine Isotope Stage 4 (MIS 4). Sediment accumulated in and shortly before the interglacial tends to be more resistant to deflation. This can be ascribed to the protection due to cemented deposits and palaeosols developed during the interglacials (Yang et al., 2003). MIS 1 has a higher proportion of stable state records than MIS 2, and in the field, it is represented by a wide occurrence of paleosols in the eastern dune fields and higher lake levels in the west sand seas during the Holocene. However, the correlation between dune activities and climate needs many more records, especially records beyond the LGM.

Currently, little onsite sedimentary evidence for aeolian sand activities during glacial periods in China has been reported. Reconstruction of the glacial palaeoenvironment in the dune fields, therefore, is still hard and ongoing work. With respect to the Last Glacial Maximum (LGM, 26.5 ka–20 ka), aeolian sand accumulation was detected in Horqin (records CHNL00041, 45–46), and it was suggested that all the stabilized and semi-stabilized dune fields in east China had been activated and extended to a much larger area (e.g. Sun et al., 1998). However, Yang et al. (2008) argued that the dune mobility in Hunshandake would be limited due to permafrost during the LGM (Zhao et al., 2014). Sandy loess deposited in the Taklamakan (record CHNL00025) and lacustrine sediments (record CHNL00149) in Badain Jaran might also indicate a less arid environment around LGM than at present.

The spatial and temporal distributions of the records for aeolian activities during the past 20 ka are summarized in Fig. 7. Most of the records show an accumulating deposition state during the deglacial epoch. However, it could not be deduced that no wet period occurred, as the records during each period are too limited to make a general conclusion for all of northern China and Mongolia. Several samples indicating stable state are dated to 18–20 ka BP (Fig. 7). There must also be some wet events not exhibited in Fig. 7 due to sampling and dating strategy. For instance, through dating the aeolian sand beneath the lacustrine sediment, it is suggested that higher lake level occurred during deglaciation in Badain Jaran (record CHNL 00153). All such wet/less arid signals are mainly detected in large dune fields in the middle and western portion of the desert belt in northern China.

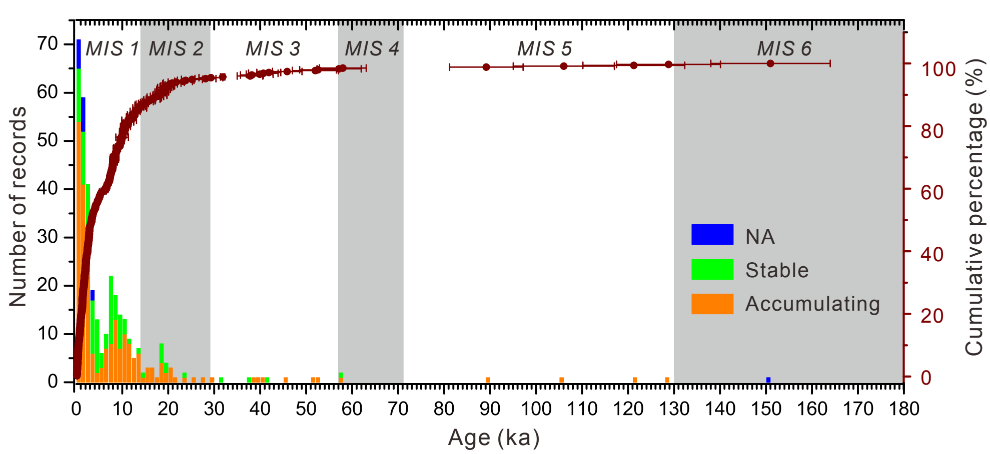

Fig. 6. Temporal distribution of aeolian sand ages at the glacial–interglacial timescales.

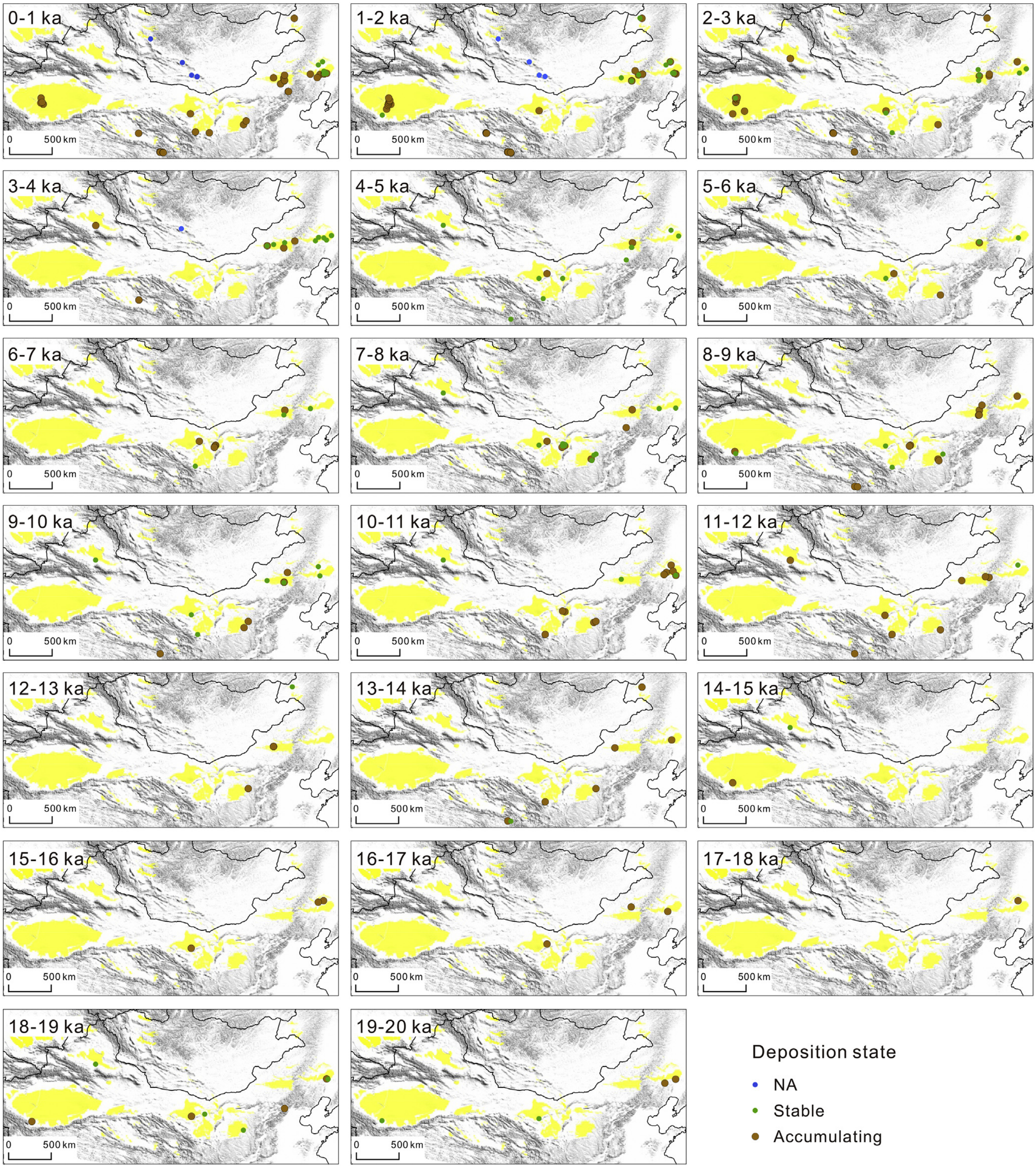

Fig. 7. Spatial distribution changes of the records over the past 20 ka.

The ratio between the number of the records for stable state and that for the accumulating state shows a much higher value during 10–3 ka BP (Fig. 8) and reaches the highest point during 5–4 ka, mirroring limited aeolian activity in general during the early-to-mid Holocene. The ratio curve exhibits a coherent relationship with the Holocene environmental changes compiled from other archives (Yang et al., 2011b), demonstrating the reliability of the dune chronologies as a useful proxy for palaeo-environmental reconstructions. Fig. 8 shows that aeolian accumulation reactivated around 3 ka BP in northern China. However, the transitional tipping point in the eastern dune fields was not synchronous with that in the west. The re-enhanced aeolian activities began at 4 ka BP in the west, while a stable state was still recorded in the east during the latest 3000 years (Fig. 8). It appears that much of the area of Horqin was covered by soil even during the last millennium (Fig. 8), corroborating the argument that human-induced desertification

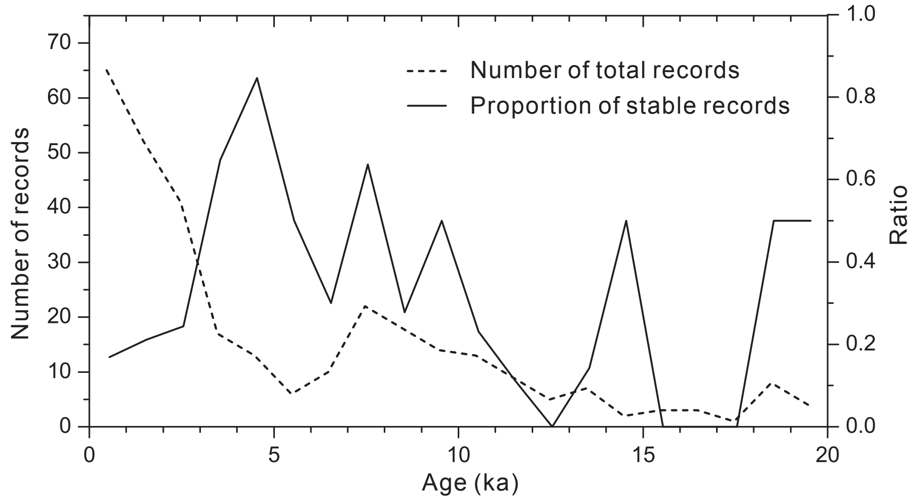

Fig. 8. Ratio between the total number of records of stable sate and the total records over the past 20 ka in China.

might be the main cause for the reactivation of this dune field (Zhu, 1998).

The large error bar of the luminescence dating for older ages (Fig. 3) implies that investigation of the aeolian sand activity at the centennial timescales should be restricted to the past 1 to 2 millennia. The number of aeolian records from middle to east China and Mongolia exhibits a fluctuating pattern during the past 2 millennia (Fig. 9). Temperature reconstruction of Beijing, ~300 km south to the desert belt, shows that there are two cold events during this period (Tan et al., 2003). One was around 1500 A.D., and the other happened 800–900 A.D. Neither the total number of the records nor the number of records with the accumulating state exhibits any substantial increase during the two periods (Fig. 9). It seems that the reconstructed moisture variation trend in northern China cannot explain the variations of aeolian records (Fig. 9). The complexity of the aeolian sand system in response to the climate changes (Lancaster, 1995), uncertainties of the reconstructed climate fluctuations and human intervention would account for the lower correlation between the palaeoclimatic curves and dune activity.

8. Conclusions

With the development and successful application of luminescence dating in the aeolian sands, over 300 records are now available for the dune fields of northern China in the INQUA Global

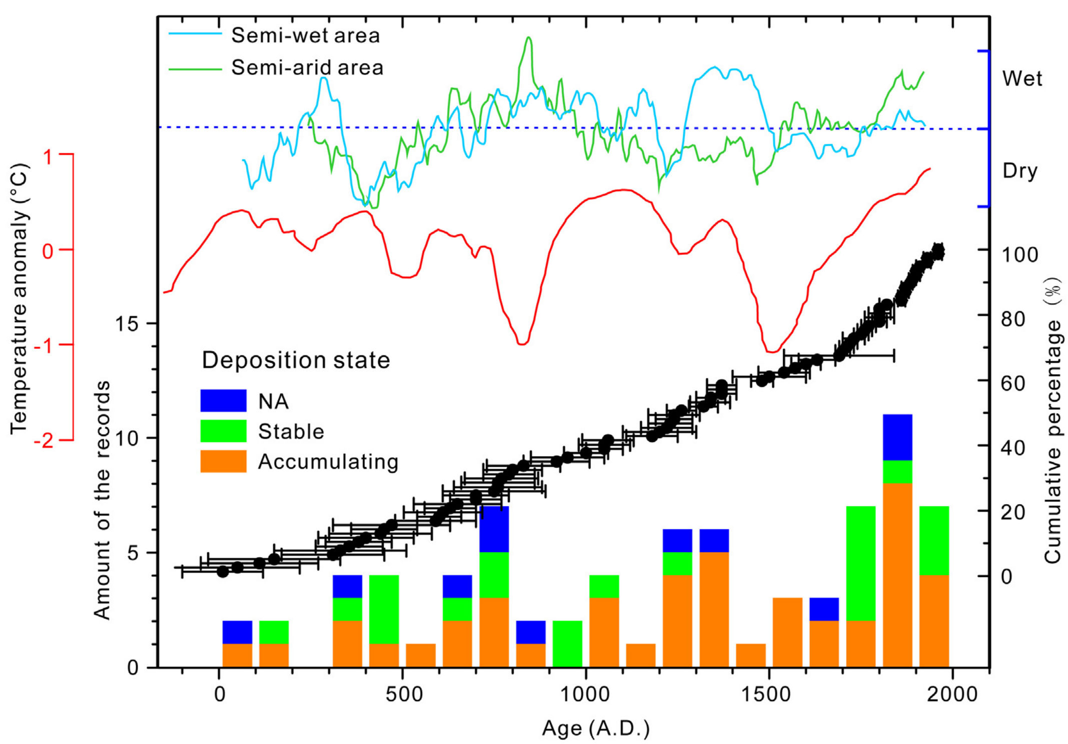

Fig. 9. Aeolian sand records (east of 100° E) variations during the last 2 millennia. The red curve is warm season (May, June, July and August) temperature reconstructed from stalagmite record in Beijing (Tan et al., 2003); and the green and blue curves are synthesized moisture conditions of semi-arid regions and semi-humid regions of northern China during the last 2 millennia, respectively (Gong and Hameed, 1991). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Digital Chronologic and Spatial Dune Database. These data provide a deep insight into the Quaternary environmental changes in the dune fields and basic knowledge about the histories of aeolian activities in the drylands in the Asian mid-latitudes. Referring to the spatial coverage, the stabilized dune fields in the eastern portion of desert belt in northern China are much better represented than the sand seas in western China. Most of the ages from the east are, however, younger than 20 ka, and little direct evidence about dune activities beyond the LGM has been found. Records from the sand seas in western China extended to the last interglacial in terms of chronology. In general, the desert sand dune activity in China is correlated with the global climate at the glacial–interglacial time scales, although many more records are needed to test and verify this correlation. Palaeoenvironments during the glacial period are more difficult to reconstruct due to potential deflation of sediments by winds, and controversies exist regarding dune activity at the LGM and deglaciation periods in northern China. During the past 2 millennia, however, there is not a significant correlation between aeolian activity and regional climate curves, mirroring the complexity of the sand dune system. The variation of the number of records indicates that aeolian sand deposition decreases during the epochs of colder climate in glacial–interglacial timescales in China and Mongolia. The lack of sedimentary evidence hampers the interpretation of the sand seas' environment during the glacial/cold periods. This should be overcome by future research. A full understanding of the Quaternary environmental changes in the dune fields of northern China requires extending both spatial and temporal coverage of the chronological data. The lack of longer records is particularly pronounced for the stabilized dune fields in the eastern portion of the desert belt in northern China. The sand seas in the west, where much larger dunes occur, offer promising research objects for extending the palaeoenvironmental records of the sand seas. The main problem with regard to these sand seas is the scarcity of data from the interior of the dune fields, and extracting paleoclimate information from these active dunes is also a challenge. Moreover, despite the occurrence of the highest dunes on the earth, few studies as yet have focused on the internal sedimentary structure of the dunes.

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