BOREAS An international journal of Quaternary research

Variations in the wind-energy regime of the Taklimakan Desert, central Asia, over the last 700 years as inferred from nebkha sedimentology and chronology

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Wang, X., Lang, L., Hua, T., Zhang, C. & Li, H. 2014 (October): Variations in the wind-energy regime of the Taklimakan Desert, central Asia, over the last 700 years as inferred from nebkha sedimentology and chronology. *Boreas*, Vol. 43, pp. 882–894. 10.1111/bor.12063. ISSN 0300-9483.

Changes in the wind-energy environment between AD 1359 and 2010 in the Taklimakan Desert (central Asia) are recorded by the evolution of Chinese tamarisk (*Tamarix taklamakanensis*) nebkhas. The carbonate component and sedimentological properties of the nebkha excavated during the study, together with AMS ^{14}C dating control, indicate that significant regional environmental changes have occurred in the central Taklimakan Desert during the last 700 years. The nebkha data presented show that in the periods of AD *c.* 1480–1560, *c.* 1640–1690, *c.* 1760–1820, *c.* 1860–1930 and *c.* 1970–1980 the Taklimakan Desert was a relatively high wind-energy environment. Although changes in the wind-energy regime in the desert were mainly in phase with fluctuations of the Siberian High, the wind systems and the variations in wind energy exhibit slight differences when compared with the Tarim Basin. Nebkhas that develop in this region originate from the surfaces of mobile dunes or sand sheets, which differs from the origins of nebkhas found in other arid regions of China.

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The Taklimakan Desert started to form at least 3.4 Ma (Sun *et al.* 2011) and is the world's second-largest shifting-sand desert. This desert is located in the Tarim Basin, and is surrounded by the Pamir Plateau, the Kunlun Mountains and the Tianshan Mountains to the west, south and north, respectively (Fig. 1). The annual precipitation in the desert is typically less than 30 mm, and evaporation exceeds 3800 mm. This desert is currently a low wind-energy environment (Wang *et al.* 2005a), and nearly all dune types contained in the various dune classification systems (Fryberger & Dean 1979; Pye & Tsoar 1990; Lancaster 1995; Livingstone & Warren 1996), including crescent, linear and star dune types can be found in their simple, compound and complex forms in different areas of the desert (Zhu 1984; Wang *et al.* 2002a). Previous studies have investigated the dynamics (Wang *et al.* 2002b, 2003a), formation (Wang *et al.* 2004) and particle size distributions (Wang *et al.* 2003b) of the simple, compound and complex dunes that develop in this region. Additionally, the evolution of the modern wind-energy environment has been described based on instrumental meteorological records from the past 50 years (Wang *et al.* 2005a, 2007; Zu *et al.* 2008). In addition, various studies of this region have examined climate change (Jin *et al.* 1994; Zhong & Xiong 1999), the evolution of the Tarim Basin (Wang *et al.* 1992), aeolian geomorphology (Zhu *et al.* 1981; Li *et al.* 1990) and the sedimentary environments of the sands and loess (Li *et al.* 1993) since the last glacial period.

Numerous studies suggest that the wind-energy regime plays an important role in the formation of aeolian morphology and of regional ecological environments in both arid and semiarid areas (Tsoar 2005; Ardon *et al.* 2009; Ashkenazy *et al.* 2012; Yizhaq *et al.* 2013). However, because of the difficulty of acquiring high-resolution proxies, and the complicated dynamics and sedimentary characteristics of the mobile dunes in the Taklimakan Desert, the evolution of the wind-energy environment over the past millennium remains poorly understood, despite previous studies that have examined climate change in the vicinity of the Tarim Basin (Li *et al.* 2006; Chen *et al.* 2010; Liu *et al.* 2011). Furthermore, despite the large scale of the climate system in the Tarim Basin, the wind system is controlled mainly by the Siberian High (Dong *et al.* 1993). However, direct evidence associating the topography and the Siberian High with the evolution of the wind-energy environment in the Taklimakan Desert for the past millennium is lacking.

In addition to the simple crescent dunes, simple linear dunes and sand sheets that make up the interdune areas of the central Taklimakan Desert, nebkhas (also referred to as coppice dunes, nabkhas, or vegetated dunes) are developed in this region (Wang *et al.* 2005a). Nebkhas are the product of basic aeolian processes

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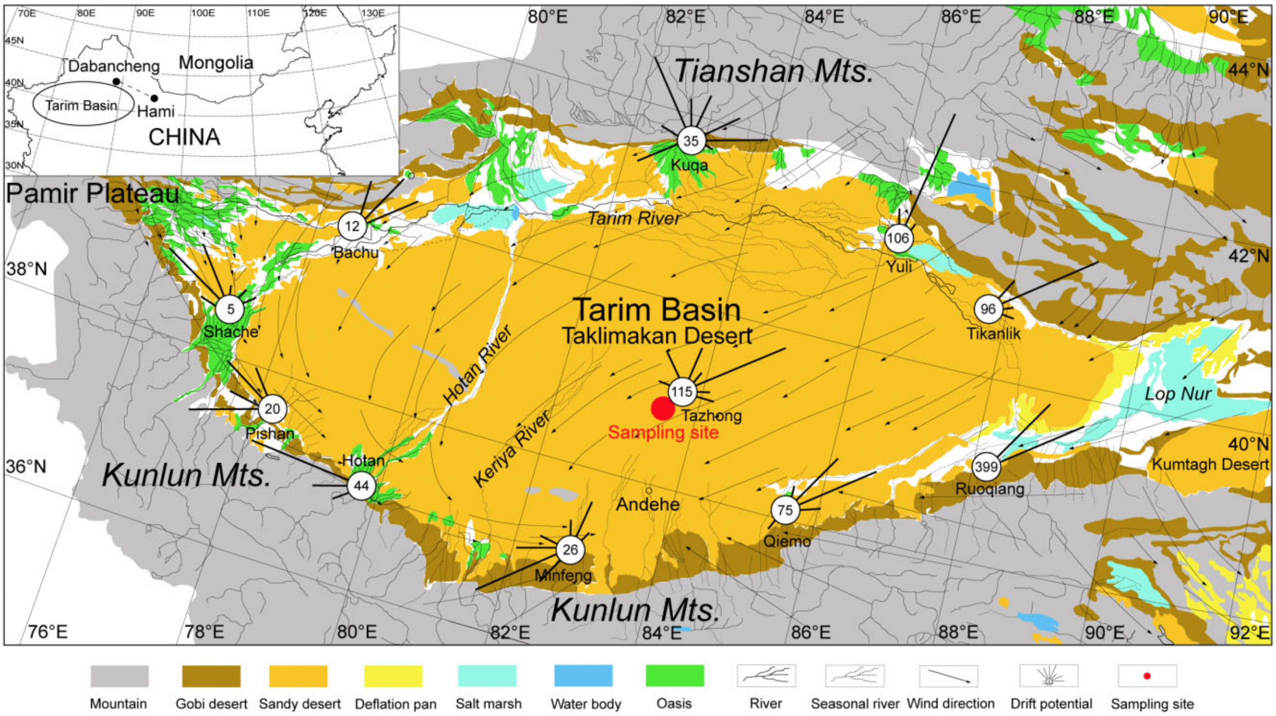

Fig. 1. Geomorphological map showing the Tarim Basin and Taklimakan Desert, the wind systems and the nebkha sampling site. The drift potential (vector unit), which is expressed as $DP \propto V^2(V-V_t)t$ (where V is the wind velocity (m s^{-1}) exceeding a threshold value at the measurement height, *t* is the proportion of the time during which the wind blew (% of the measurement duration) and V_t is the threshold wind velocity at the measurement height), were calculated following Fryberger & Dean (1979), Wang *et al*. (2005a) and Zu *et al*. (2008). This figure is available in colour at http://www.boreas.dk.

(Tengberg 1995; Hesp & McLachlan 2000; Langford 2000), and nearly all nebkhas in the study area have the Chinese tamarisk (*Tamarix taklamakanensis*) as their nucleus. In the central Taklimakan Desert, the aeolian materials deposited within nebkhas are derived from adjacent mobile dunes and interdunes. As an incipient nebkha forms, *T. taklamakanensis* traps aeolian sediments, which leads to the enlarging of the nebkha, and the sediments found within such dunes can record environmental changes over the period of deposition. As wind plays a key role in the dynamics of nebkhas, the regional evolution of the wind-energy environment can be reconstructed by analysing the sediments deposited within the nebkhas. This study uses sediments sampled from a nebkha in the central Taklimakan Desert to reconstruct changes in the wind-energy environment (with a resolution of four years) and considers the evolution of the wind environment and related environmental conditions in this region over the past 700 years.

Sampling site and analytical methods

Our sampling site was located in the central Taklimakan Desert (Fig. 1). According to instrumental records (averaged over the period 1999–2008), the mean annual temperature, precipitation and evaporation, measured at a station approximately 20.7 km from the sampling site, were 12.3°C, 27.8 mm and 3835.4 mm, respectively. In this region, the nebkha community is extensively developed in the interdunes of the mobile megadunes. Nebkhas containing a Chinese tamarisk (*T. taklamakanensis*) nucleus and sediment accumulated from adjacent mobile dunes and interdunes are near-circular in shape, and are scattered along the interdune areas of the mobile megadunes (Fig. 2A). In the sampled interdune area, the vegetation cover of the nebkhas is approximately 50 to 60% during the growing season (April–October) and 20 to 30% during the other seasons (Wang *et al*. 2005a). Although it is not clear whether wind erosion has occurred on the surfaces of the nebkhas, previous studies (Wiggs *et al*. 1994, 1995) have suggested that the vegetation cover exceeds 14%, the amounts of aeolian deposits were greater than the extent of erosion. In addition, previous studies (Liu *et al*. 2011) have suggested that there have been no extreme arid events during recent centuries in the Tarim Basin. Therefore, despite there being variations in the vegetation cover during different periods, the regional climatic conditions have ensured that the nebkhas have developed continuously since they first formed.

On 21st October 2010, we sampled a *T. taklamakanensis* nebkha located on an interdune (latitude

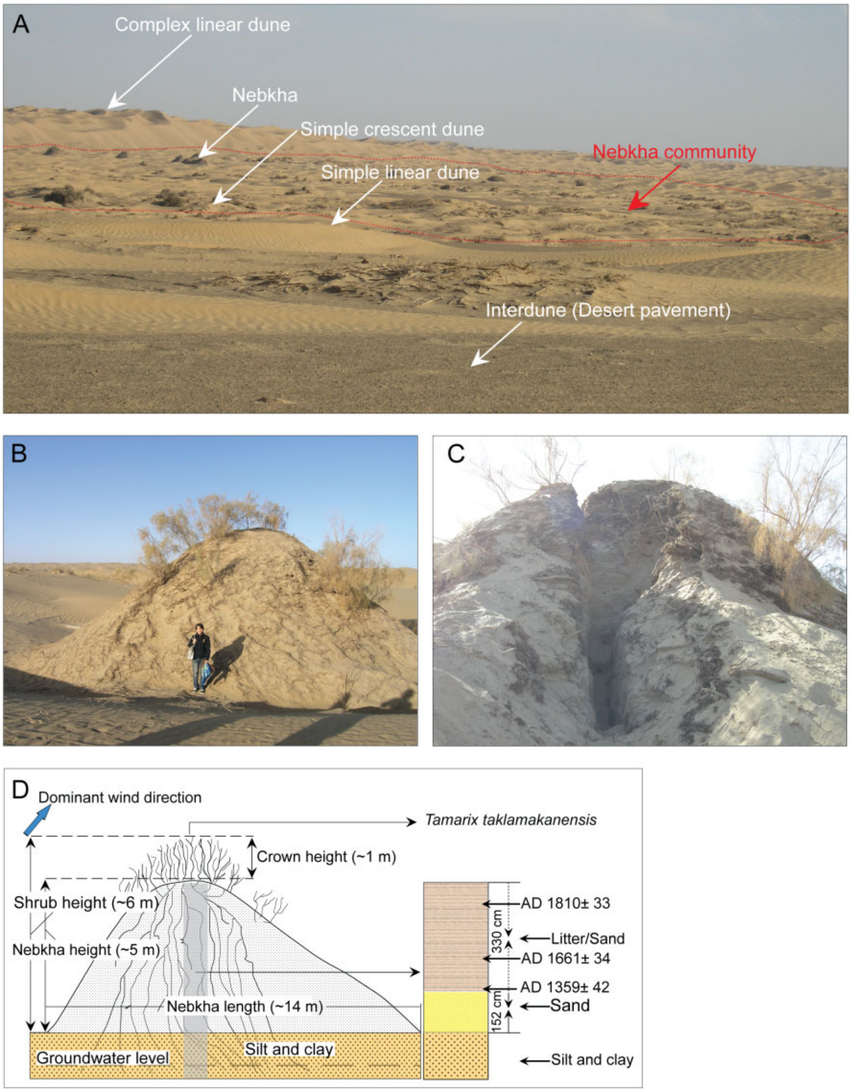

Fig. 2. Dune systems of the central Taklimakan Desert (A) and the sampled nebkha. The photographs of the dune systems were taken approximately 30 km north of the nebkha sample site before excavation (B) and after excavation (C). D. A diagram of the profile. This figure is available in colour at http://www.boreas.dk.

38°51.607′N, longitude 83°30.554′E). The nebkha was approximately 5 m tall, 14 m in diameter and round in shape (Fig. 2B). The vegetation cover was approximately 30%, even at the end of the growing season in late October. In this region, the *T. taklamakanensis* cover is greater on the southern side of the nebkhas than on other sides because the prevailing winds blow from the northeast. Therefore, we excavated the dune to reveal a clean vertical profile through the full height of the northern side. From the crest of the dune towards the bottom, we observed distinct cross-stratification in the leaf litter of the *T. taklamakanensis* and aeolian sediments, especially in the uppermost region of the profile (Fig. 2B, C). We collected mixed sediments and litter at 2-cm intervals (the maximum resolution possible in the field) throughout the profile. From the top of the dune to a depth of 270 cm, the litter strata of the *T. taklamakanensis* were sampled continuously. However, the presence of litter was not continuous between depths of 272 and 330 cm, and no litter was visually observed at depths below 332 cm. We collected a total of 241 samples, reaching a final depth of 482 cm. In addition to the mixed sediment and litter sampling, we also collected litter samples from within the nebkha at depths of 160, 238 and 328 cm for accelerator mass spectrometry (AMS) ^{14}C dating (Fig. 2D).

After the *T. taklamakanensis* litter had been separated from the sediment by sieving, we analysed the particle size of the sediment using a Mastersizer Laser 2000 (Malvern Co. Ltd, Malvern, UK; sample range 0.02–2000 μm in diameter) and measured the carbonate content of the samples, and performed AMS ^{14}C dating. Before obtaining particle size measurements, we immersed the sediments in 10% H_2O_2 and then in 12.7% HCl to remove any plant debris and to disperse aggregates within the sediments. The sample residue was finally treated with 10 mL of 0.05 M $(NaPO_3)_6$ on an ultrasonic vibrator for 10 min to facilitate dispersion prior to grain size analysis. Repeated particle size measurements on each sample revealed only slight differences (<0.5%). AMS dating was performed at the Xi'an AMS Centre, Chinese Academy of Sciences. We followed the dating methodology, instrumentation and calculation of measurement errors as described by Zhou *et al.* (2007). The ^{14}C age of each sample was calculated using the methods of Stuiver & Polach (1977), and the ages were calibrated using Calib 6.1.0 (Stuiver & Reimer 1993) and the IntCal09 calibration data set (Reimer *et al.* 2009). In addition, the carbonate content of the sediments was measured using the modified gas evolution method on a standard Bascomb Calcimeter (Bascomb 1961; Machette 1986).

Results

When excavated, the studied dune was 4.82 m high. The stratigraphy of the sampled nebkha includes three main sediment types. The first type is found below 482 cm depth, where lacustrine sedimentation has developed due to ephemeral water-logging, with the dominant fractions being clay and silt. The second type is found from 482 to 332 cm, and consists of aeolian sands. The third type is found from 330 cm depth to the nebkha crest, and comprises *T. taklamakanensis* litter mixed with aeolian sands (Fig. 2D). We conclude that after the drying of ephemeral lakes in interdune areas, small-scale mobile dunes, such as simple crescent forms or sand sheets, firstly developed. After the mobile dunes increased to heights of approximately 1.54 m, the high moisture availability (Lang *et al.* 2013) promoted the growth of *T. taklamakanensis* on the surface of the mobile dune and, subsequently, the nebkha began to form and continued to develop at this site.

The ephemeral litter derived from *T. taklamakanensis* within the nebkha provided excellent material for establishing a chronology. Given that we sampled the nebkha during the defoliate season of *T. taklamakanensis* (the end of October), we deduced that the surface litter was the product of the current year (2010). AMS dating provided ages at depths of 160, 238 and 328 cm of AD 1810, 1661 and 1359, respectively, and reveals that the nebkha originated at about AD 1359 (Table 1). In addition, by interpolation, our results indicate that the net deposition rates (differences between the deposition depth and erosion depth) for the periods AD 1359 to 1661, 1661 to 1810 and 1810 to 2010 were 0.30, 0.52 and 0.79 cm a^{-1}, respectively, and that the average deposition rate throughout the profile was 0.50 cm a^{-1}. The average resolution of the section of the profile containing the Chinese tamarisk litter is 3.97 years, with a maximum value of 2.54 years. Therefore, by using linear interpolation between the adjacent calibrated radiocarbon ages, we established the chronology of the nebkha.

Table 1. AMS radiocarbon dates obtained from the nebkha sediment profile.

Sample ID	Depth (cm)	^{14}C age (a BP)	Calibrated range (2σ) (AD)	Calibrated age (2σ) (AD)
TK80	160	152±33	1666–1953	1810
TK119	238	251±34	1519–1802	1661
TK164	328	581±42	1297–1421	1359

Particle size variations in the nebkha profile are shown in Fig. 3. Throughout the profile (from a depth of 328 cm to the nebkha crest), the average contents of the fractions <20, 20–63, 63–100 and >100 μm are 48.86 (SD: 6.47), 35.56 (SD: 3.17), 12.57 (SD: 2.73) and 3.01% (SD: 1.29%), respectively. The results also show that after the nebkha became established, and as the dune height increased from 1.56 to 4.82 m between approximately AD 1360 and 2010, the amount of coarse sediment (>100 μm) present decreased, whereas the proportion of the sediments in the <20, 20–63 and 63–100 μm size fractions increased as the nebkha developed. However, there were fluctuations from AD 1365 to 1380, 1440 to 1460, 1520 to 1540, 1640 to 1680 and 1860 to 1920. Throughout the profile, the average particle sizes vary between 87 and 145 μm, with a mean of 99 μm and an SD of 8 μm. Particle size variation in the profile is positively correlated with variations in the >100 μm fraction, with a Pearson correlation coefficient of 0.976 (at the 0.01 level; Table 2). However, particle size is negatively correlated with the size fractions of <20, 20–63 and 63–100 μm, with Pearson correlation coefficients of –0.751, –0.874 and –0.971, respectively. These results suggest that during the formation of the nebkha, particles transported by saltation (particle size typically 100–500 μm) from adjacent areas were the dominant sediment source for the nebkha. In addition, our results reveal that there were also slight fluctuations in the carbonate content during the formation of the nebkha. Throughout the nebkha profile, the average carbonate content is 11.40%, with an SD of 0.75%. The Pearson correlation coefficients between the carbonate contents and the contributions from the <20, 20–63, 63–100 and >100 μm size fractions are 0.153, 0.133, 0.166 and –0.164, respectively, suggesting that most of the carbonates are contained within the fine fraction of the sediments.

Discussion

Over recent centuries, variations in the wind regime and vegetation cover provided by *T. taklamakanensis* resulted in varying nebkha deposition rates, and such data can be used as excellent proxies for palaeoclimatic and palaeoenvironmental change in both arid and semiarid areas. For instance, Wang *et al.* (2008, 2010)

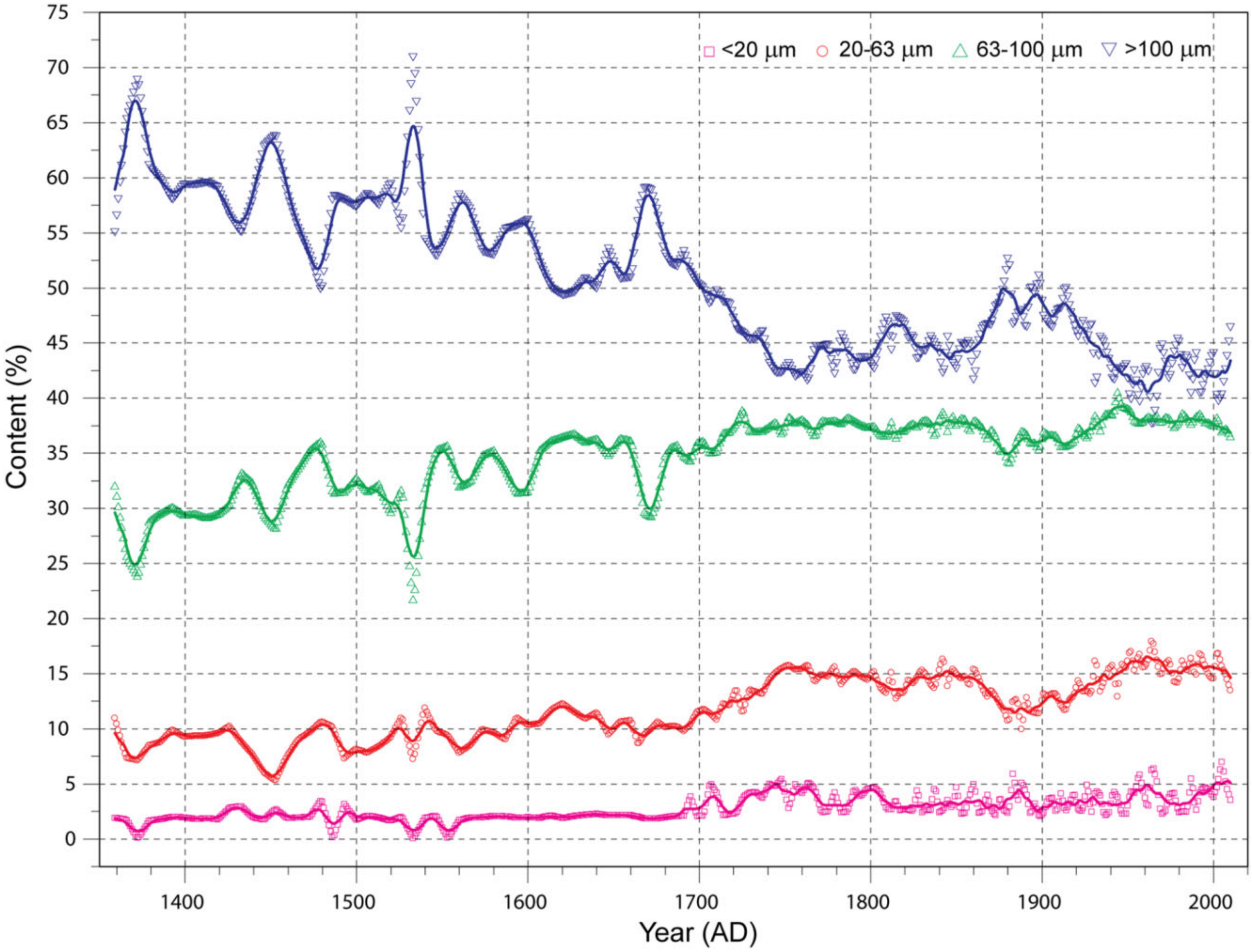

Fig. 3. Particle size distributions along the nebkha profile from AD 1359 to 2010. The results show that from approximately AD 1360 to 2010, the fraction in the >100-μm size range decreased. The annual values were acquired by linear interpolation and smoothed with a 10-point running mean. This figure is available in colour at http://www.boreas.dk.

used multiple proxies, including particle size distributions, carbonate, total organic carbon (TOC) and total nitrogen (TN) contents in sediments, and $\delta^{13}C$ values in the litter of nebkhas to reconstruct wind-energy variations, moisture fluctuations and sediment availability for the Ala Shan Plateau over several centuries. Seifert *et al*. (2009) used the coarse fraction percentages of nebkha sediments deposited on different flanks of dunes to determine variations in the palaeowind directions in the south-central USA. Xia *et al*. (2005) and Zhao *et al*. (2011) analysed TOC, TN contents and C/N ratios in sediments and $\delta^{13}C$ values in the litter of nebkhas to reconstruct climatic and environmental changes in Lop Nur during the past two centuries.

Table 2. Pearson correlations between different particle size parameters from the aeolian sediments.

Pearson correlations						
	<20 μm	20–63 μm	63–100 μm	>100 μm	Medium (μm)	Mean (μm)
20–63 μm	0.709*					
63–100 μm	0.634*	0.825*				
>100 μm	–0.779*	–0.946*	–0.951*			
Median (μm)	–0.751*	–0.874*	–0.971*	0.976*		
Mean (μm)	–0.647*	–0.667*	–0.923*	0.849*	0.918*	
$CaCO_3$ (%)	0.153*	0.133*	0.166*	–0.164*	–0.195*	–0.173*

*Correlation is significant at the 0.01 level (two-tailed).

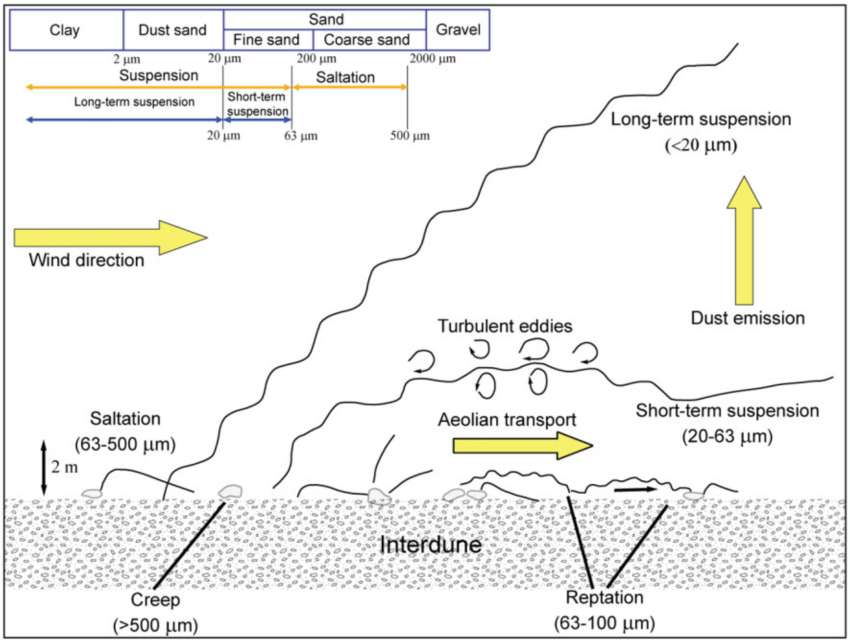

Fig. 4. Particle motion patterns under wind activity (modified from Pye & Tsoar 1990). This figure is available in colour at http://www.boreas.dk.

However, once the threshold of aeolian movement has been exceeded and particles become entrained by the wind, they travel in four distinct ways, which, in order of increasing velocity, are creep, saltation, reptation and suspension (Livingstone & Warren 1996). Of the four modes of travel, saltation is the key process, as most of the 63–500 μm fraction travels in this manner (Pye & Tsoar 1990; Kok *et al.* 2012; Fig. 4), and particles of this fraction are the principal component of aeolian dunes (Lancaster 1995). However, during the formation of nebkhas, in addition to the impact of vegetation on sand transport (Hesp & Martinez 2008), there are very complicated patterns of particle transport. For example, in the Taklimakan Desert, although the development of vegetation on the nebkha surfaces forces the particles to be deposited on the dune surfaces, the airflows on the nebkha surfaces are complex (Fig. 5A). In addition, during the process of nebkha formation, the average saltation heights of particles vary as a result of variations in wind velocity and particle size (Fig. 5B), and the grains travelling by saltation are finer. Moreover, as the nebkha increases in size, the slope angles and height of the nebkha also increase, which raises the threshold of particle entrainment (Iversen & Rasmussen 1994). Therefore, as nebkhas develop, the amount of material within the coarse fraction and the particle size of the sediments both decrease.

From its stratigraphical profile alone, we cannot determine which sediments were deposited on which slope of a mobile dune, as there are large differences in particle size distributions between the different slopes of mobile dunes (Wang *et al.* 2003b). In contrast, nebkhas are anchored dunes, which means that the trends preserved in the particle size distributions of their sediments can be related to variations in the wind-energy environment. Although the coarse fraction and median particle size both decreased over time as the studied nebkha developed, there were still notable increases in particle size during different phases of its development (Fig. 6), indicating that there were episodes or phases during which the strength of regional winds increased. Although we are unable to use variations in the coarse fraction within the nebkha sediments to estimate the mean wind velocity or drift potentials in each of these phases, our results show that from the AD 1480s to the 1560s, the 1640s to the 1690s, the 1760s to the 1820s, the 1860s to the 1930s and the 1970s to the 1980s (S1 to S5 in Fig. 6), the Taklimakan Desert was under the influence of a relatively high wind-energy regime, which was recorded by the nebkhas that formed in this region.

Comparisons between the median particle size and increasing proportion of coarse sediments and the instrumental annual wind velocity obtained from different periods indicate relatively high wind-energy environments (Fig. 7). The precision of AMS ^{14}C dating does not allow us to compare particle size trends with the instrumental wind velocity records year to year. However, assuming that the lag or lead of the coarse fraction does not exceed 10 years, it appears that the coarse fraction, the median particle size values and the instrumental wind velocity all follow the same trends after AD 1810. During the last 700 years, the coarse fraction of the nebkha sediments was in phase with periods of relatively high wind energy.

There are no significant positive correlations between high wind energy and the proportion of fine sediment.

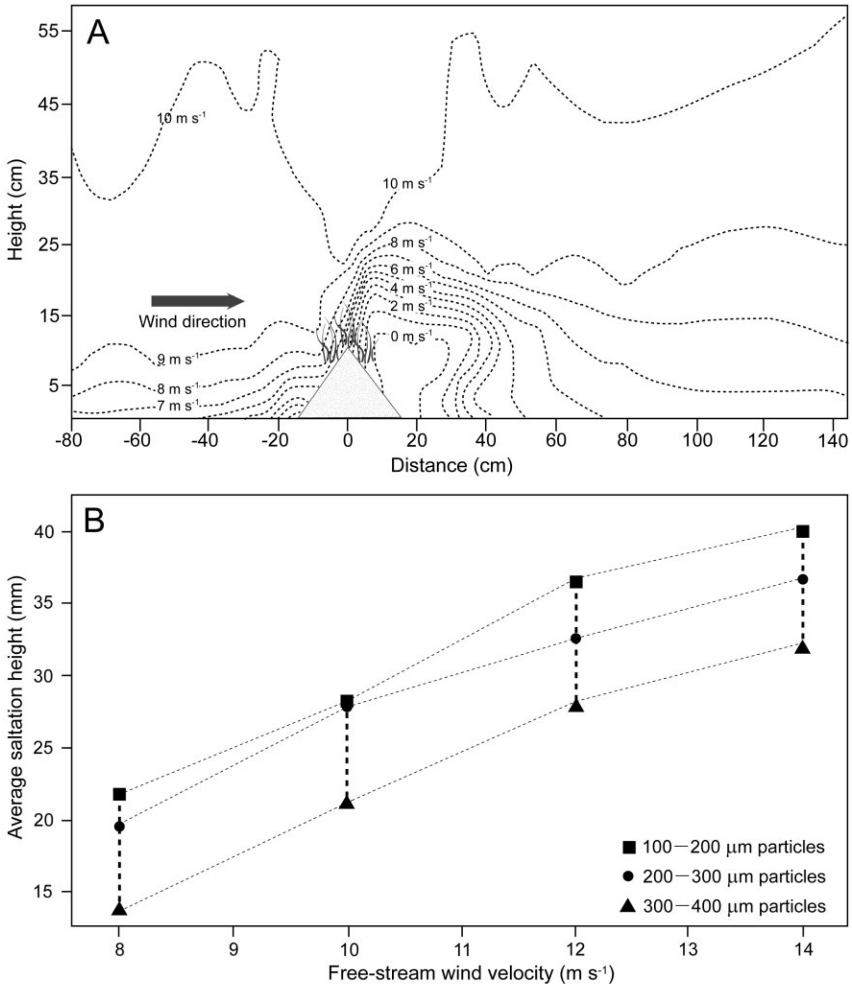

Fig. 5. A. Airflow patterns on the nebkha surfaces (based on data from Wu *et al.* 2006). B. Variation in average saltation height with wind velocity and particle size (based on data from Dong *et al.* 2006) acquired from wind tunnel experiments.

For instance, although the amount of sediment in the fine fraction increases with increasing near-surface wind velocity, there is a weak negative correlation between the concentration of fractions <10 μm and wind velocity (Simpson 1990), and the fine fraction (i.e. <50 μm) initially decreases as wind velocity increases (Harrison *et al.* 2001; Jones *et al.* 2010; Wang *et al.* 2012). In the Taklimakan Desert, high near-surface winds may decrease the amount of fine material deposited within the nebkhas. As a result, the proportion of sediments in the fine fraction cannot be used as a proxy for changes in the wind-energy environment in this region.

Variations in carbonate content are affected by the source of the carbonates, such as mollusc shells (An *et al.* 2004), allochthonous aeolian inputs (Antoine *et al.* 1999) or degassing and/or evaporation of soil moisture (Dever *et al.* 1987). Carbonate content has also been used as a proxy for precipitation (Gallet *et al.* 1996; Fang *et al.* 1999) and as an indicator of the intensity of weathering and pedogenesis (Yang *et al.* 2006). However, analysis of caliche formation in desert soils (Schlesinger 1985) and surface materials in arid areas (Wang *et al.* 2005b) showed no significant correlation between carbonate content and annual precipitation. In our study area, the annual precipitation is only 27.8 mm, whereas evaporation exceeds 3800 mm. There are consistent trends amongst carbonate content, instrumental precipitation, temperature and evaporation. Figure 8 shows that variations in the carbonate contents of nebkha sediments show similar trends to variations in evaporation. In addition, in extremely arid areas, such as the central Taklimakan Desert, evaporation is the key factor controlling chemical weathering (Liu *et al.* 2007). Therefore, high evaporation rates in the past may have enhanced weathering intensity and increased the carbonate content of the fine fraction available for nebkha formation in this region.

The carbonate content of the mobile dune sediments below the nebkha sediments is 11.30%, compared with 11.40% throughout the nebkha profile. These values indicate that both physical and chemical weathering were very weak in this extremely arid area. As most

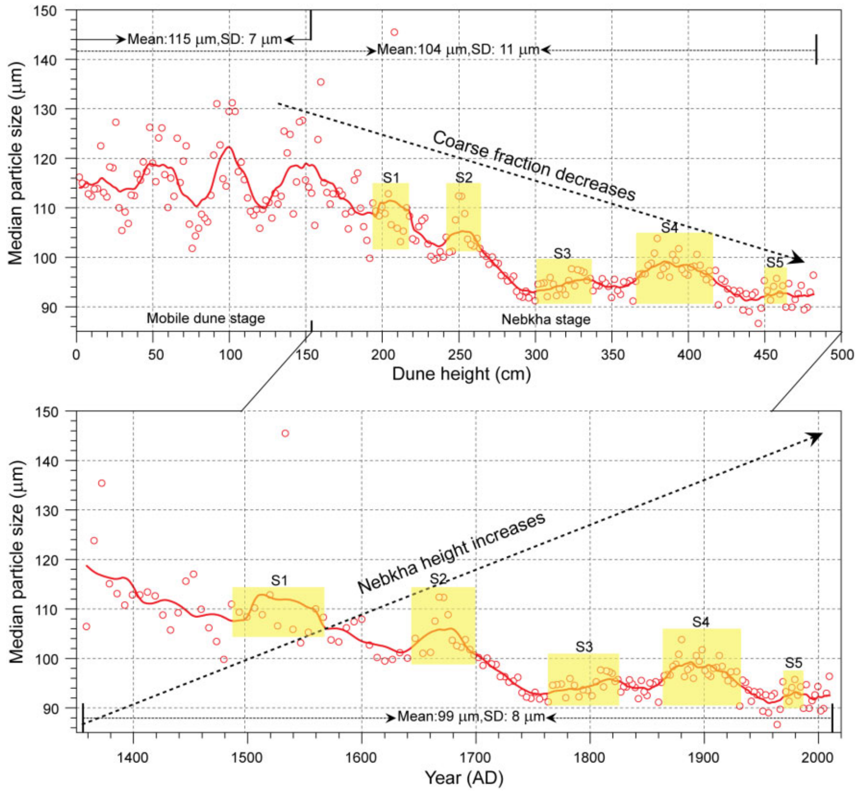

Fig. 6. Median particle size trends along the dune profile and periods of high-wind-energy environments (S1 to S5) in the Taklimakan Desert over the past 700 years, inferred from the formation of nebkhas (smoothed with a 10-point running mean). This figure is available in colour at http://www.boreas.dk.

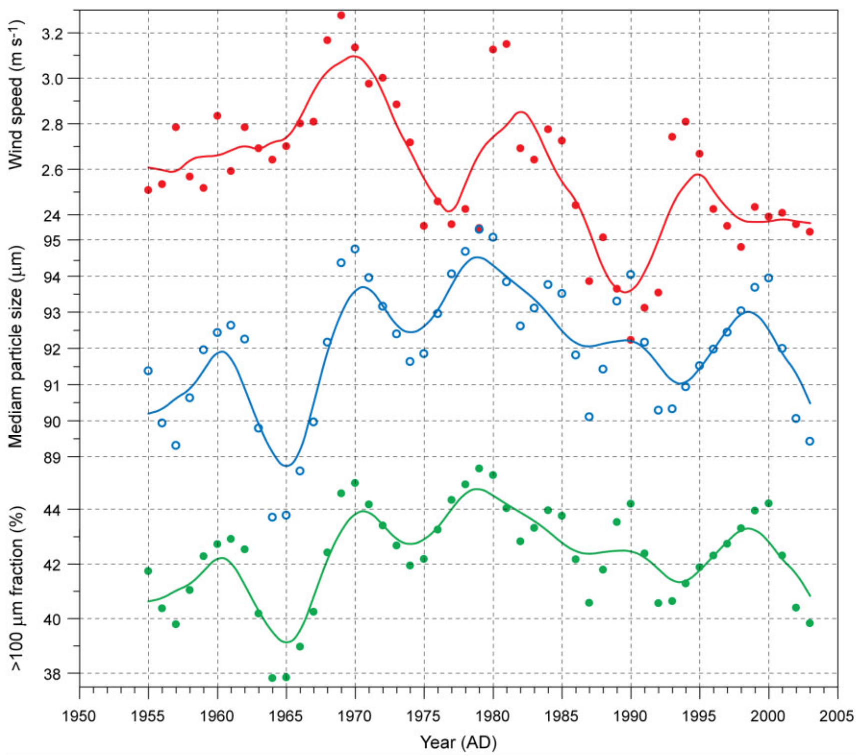

Fig. 7. Measured annual mean wind velocity data from 1955 to 2003 compared with the coarse fraction (>100 µm) and median particle size (µm) of the nebkha profile. The annual values of the coarse fraction (>100 µm) and the median particle size were calculated using linear interpolation between measurements, with a resolution of 2.54 years. The wind data were acquired from Ruoqiang meteorological station, which is upwind of the sampling site and whose wind variations are in phase with those at the sampling site. The station location is shown in Fig. 1. This figure is available in colour at http://www.boreas.dk.

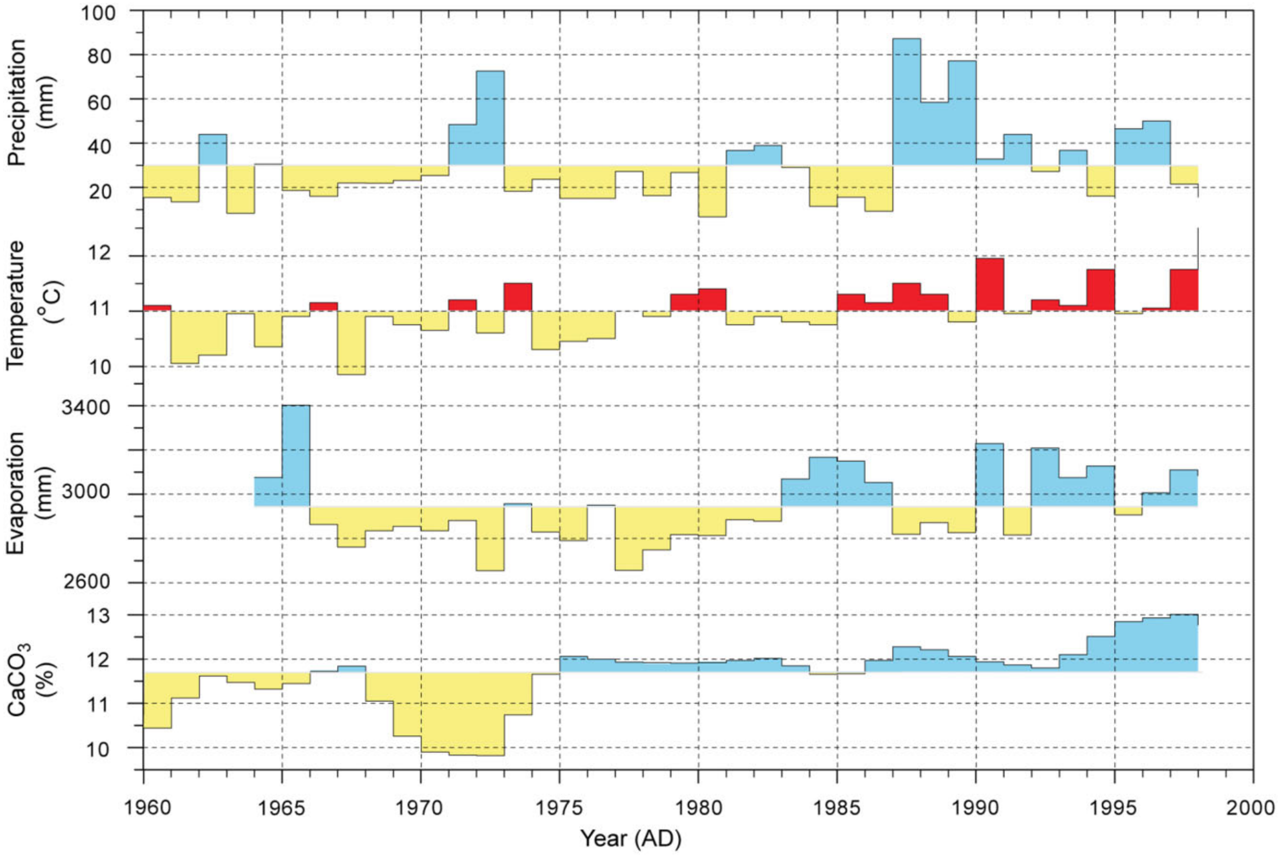

Fig. 8. Measured annual temperature, precipitation and evaporation data from 1960 to 1998 compared with the $CaCO_3$ content of the profile. The annual values of $CaCO_3$ were determined by linear interpolation between measurements, with a resolution of 2.54 years. The temperature and precipitation measurements represent the averages of the values at the Minfeng and Andehe meteorological stations (the stations nearest to our sampling site). Owing to the lack of data available from the Andehe station, the evaporation data were taken from the Minfeng station. The station locations are shown in Fig. 1. This figure is available in colour at http://www.boreas.dk.

carbonate within the nebkhas is derived from adjacent areas, its content is indicative of the environmental conditions that prevailed during nebkha deposition. We also observed a positive correlation of carbonate content with the fine fractions of the aeolian sediments, but a negative correlation with the coarse fractions (Table 2), suggesting that weathering may increase fine-fraction availability for aeolian transport. Despite the generally small differences in the carbonate content of the nebkha sediments, four periods of relatively high intensity weathering are detected over the past 700 years (S1 to S4 in Fig. 9). Our results demonstrate that from the AD 1480s to the 1640s, the 1700s to the 1800s, the 1830s to the 1850s and the 1970s to the present, the Taklimakan Desert experienced periods of relatively high availability of fine sediment, which provided more fine particles for the formation of nebkhas in this region.

Over the past 700 years, variations have occurred in the wind regime of the Taklimakan Desert. Wind systems in the Taklimakan Desert, especially in late winter and early spring, which is the windiest season of the year, are controlled mainly by the cold, low-level winds associated with cold air related to the Mongolian anticyclone (Pye & Zhou 1989), and by local wind systems controlled by topography (Zhu *et al.* 1981; Uno *et al.* 2005; Zu *et al.* 2005). For instance, north-west winds associated with the westerlies blowing over the Pamir pass, and the northeast and north-northeast winds associated with the westerlies from the Dabancheng-Hami pass, blowing across the northern slopes of Tianshan Mountains, form an easterly jet at a lower level (Fang *et al.* 2002). Both wind systems are controlled mainly by variations in the intensity of the Siberian High over central Asia (Meeker & Mayewski 2002), but there are some discrepancies between the variations in wind in the Taklimakan Desert and the fluctuations of the Siberian High (Fig. 10).

The processes that formed the nebkhas in the central Taklimakan Desert may differ from those of nebkhas found in other arid areas of China. For instance, nebkhas on the western Inner Mongolia Plateau usually originate from wadis (Wang *et al.* 2008, 2010), whereas in the central Taklimakan Desert they origi-

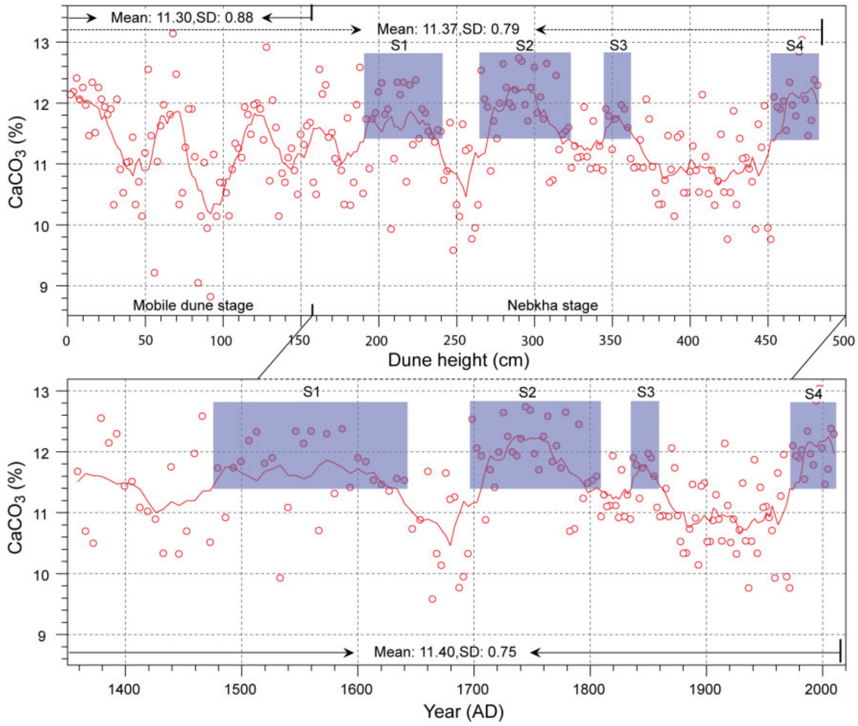

Fig. 9. Carbonate content trends along the dune profile and interpreted periods of increased weathering (S1 to S4) in the Taklimakan Desert over the past 700 years (smoothed with a 10-point running mean). This figure is available in colour at http://www.boreas.dk.

nate from the surfaces of mobile dunes or sand sheets. In this region, based on field surveys and sediment sampling, we postulate that there were at least four stages of nebkha formation in the central Taklimakan Desert (Fig. 11). The first stage was the disappearance of ephemeral surface water on the interdunes, which led to the development of mobile simple dunes, such as linear dunes and sand sheets. Subsequently, in the

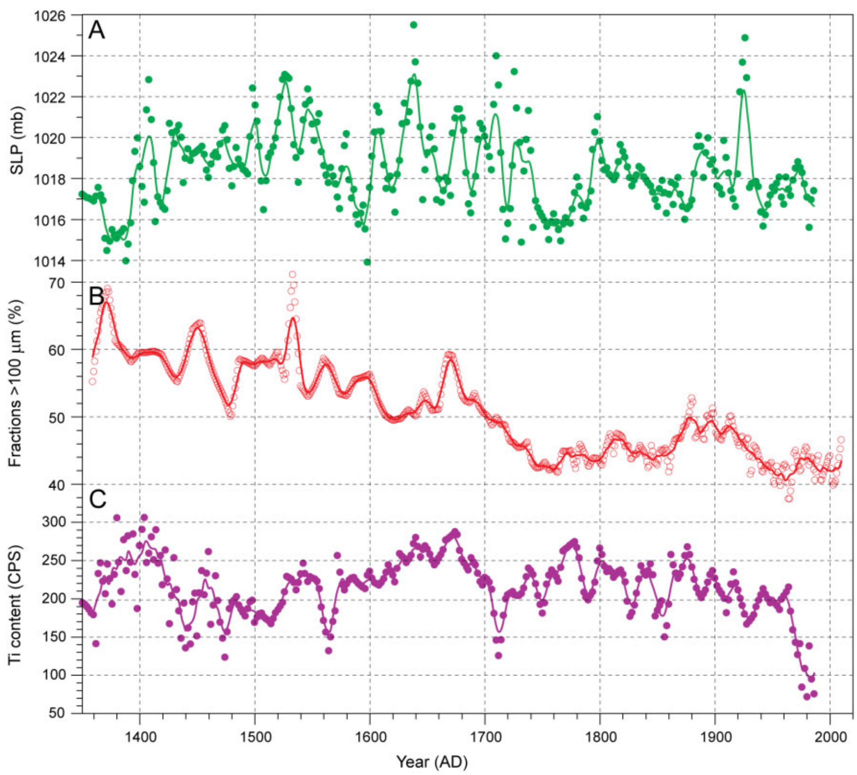

Fig. 10. Comparisons of (A) the reconstructed Siberian High SLP (sea level pressure) 29 proxy series, based on a three-year resampled GISP 2 (Greenland Ice Sheet Project Two) log (nssK) series calibrated with, and extending, the instrumental record from 1899–1986 (after Meeker & Mayewski 2002) of (B) the titanium record of Core CH1 from the Large Aral Sea, which indicates wind intensity variations in the Aral Sea area (after Sorrel *et al.* 2007). C. Variations in wind-energy environment indicated by the particle size fraction >100 μm within the nebkha profile in the Taklimakan Desert. All series were smoothed using a 10-point running mean. This figure is available in colour at http://www.boreas.dk.

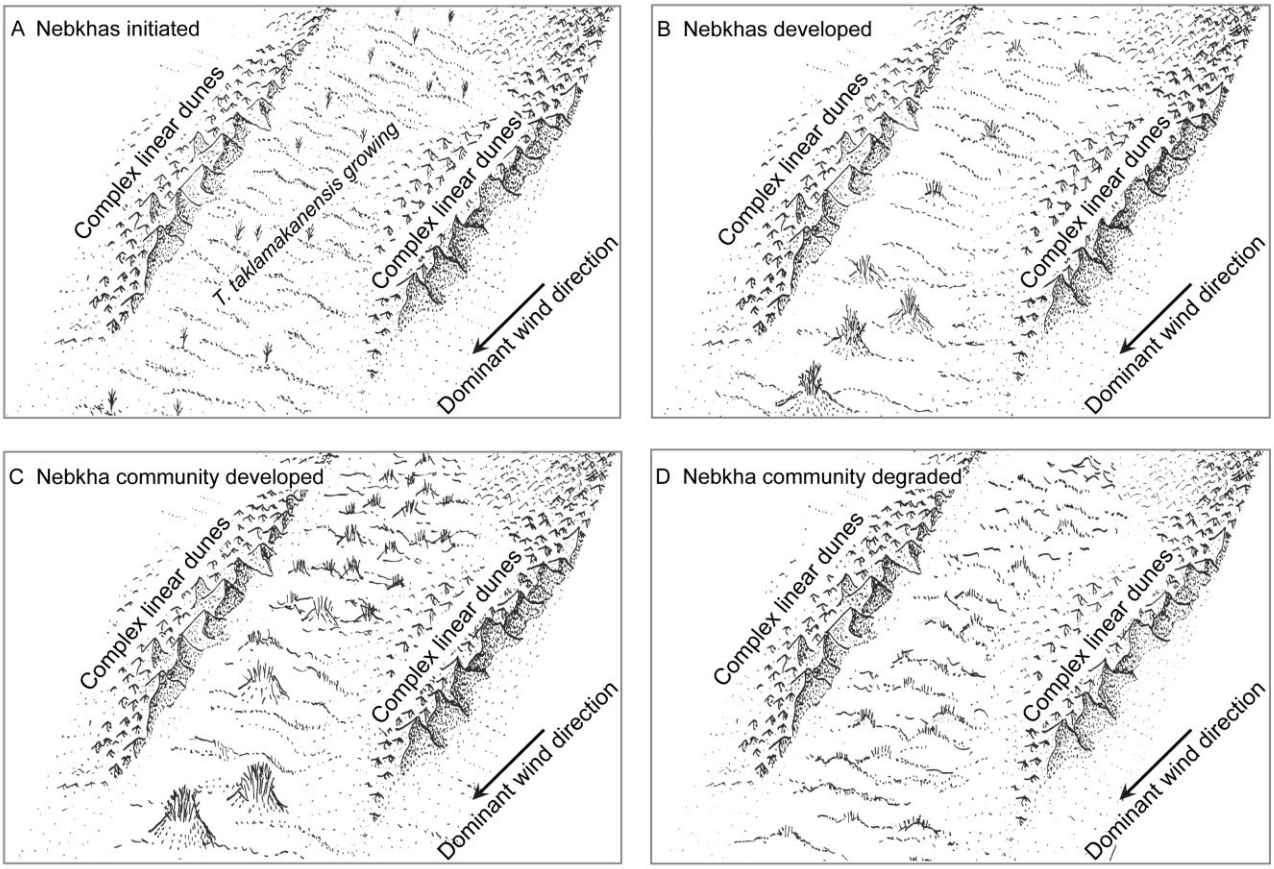

Fig. 11. Schematic illustration of the stages of nebkha development based on changes in size and dimensions. A. Nebkha initiation. B. Increase in the size of nebkha. C. Development of nebkha community. D. Degradation of nebkha community.

second stage *T. taklamakanensis* became established on the surfaces of the simple mobile dunes or on sand sheets in response to high moisture availability (Lang *et al*. 2013; Fig. 11A), and aeolian sediments were deposited around the *T. taklamakanensis*, forming the early nebkha dunes (Fig. 11B). In the third stage, as aeolian deposits from adjacent mobile dunes and interdunes rapidly accumulated, nebkha communities developed on the interdunes of the megadunes, and the changing character of the sediments deposited within the nebkhas recorded environmental changes in the region. Nebkha development was controlled mainly by variations in wind patterns and moisture conditions, which influenced the extent of *T. taklamakanensis* (Fig. 11C). Finally, in the fourth stage, as nebkhas reached their maximum size or as moisture conditions and other environmental drivers of *T. taklamakanensis* deteriorated, the nebkhas degraded and evolved into sand sheets or scattered mobile dunes (Fig. 11D).

Conclusions

The evolution of the wind-energy environment from AD 1360 to 2010 in the Taklimakan Desert (central Asia) is recorded by the development of Chinese tamarisk (*T. taklamakanensis*) nebkhas. Our results demonstrate that over the last 700 years, the proportion of aeolian sediments in the >100-μm fraction and the median particle size decreased as the nebkhas developed. High volumes of sand were transported in the Taklimakan Desert during several periods, including the AD 1480s to the 1560s, the 1640s to the 1690s, the 1760s to the 1820s, the 1860s to the 1930s, and the 1970s to the 1980s. Although the variations in the other proxies, such as carbonate content, may be closely related to precipitation and other indices, the carbonate content of the nebkha sediments reflects mainly the variations in evaporation, and indicates the intensity of physical and chemical weathering in this region. Owing to the development of the local wind system, there are differences in the variations of the wind-energy regimes between the Taklimakan Desert and the fluctuations of the Siberian High. In the central Taklimakan Desert, nebkhas originate from the surfaces of mobile dunes or sand sheets, which differs from the formational processes of nebkhas that develop in other arid regions of China. Overall, the sedimentological characteristics of nebkhas combined with AMS ^{14}C chronology provide a basis for reconstructing environmental changes in the Taklimakan Desert.

Acknowledgements. – This work was supported by the National Natural Science Foundation of China (NSFC 41071008 and 41225001). The ^{14}C dating was carried out by X. Lu of the Xi'an AMS Centre, Institute of Earth Environment, Chinese Academy of Sciences. Special thanks are given to J. A. Piotrowski for his detailed edits on this manuscript. We thank R. T. Cox and other anonymous reviewers for their constructive comments on this manuscript.

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