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Invited Review

Quaternary environmental changes in the drylands of China – A critical review

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ABSTRACT

This paper reviews our current understanding of Quaternary climate and landscape changes in the desert areas of northern China, a key portion of the middle-latitude drylands on Earth. Combining earlier studies with our recent research and experience, we offer a comprehensive picture of the state of Chinese deserts during the Quaternary and, in the interest of enhancing future research, identify knowledge gaps and areas of uncertainty.

Lacustrine deposits found over an area ranging from China's western Taklamakan Desert to the eastern Hunshandake Sandy Lands suggest that extensive lakes occurred in China's deserts during the Pleistocene. Analysis of digital elevation models from SRTM (Shuttle Radar Topography Mission) data supports this interpretation and shows the significant extent of these former lakes. New estimates of mean annual evaporation of ca. 1000 mm from lake surfaces and ca. 100 mm from land surfaces, confirms that local and regional rainfall is critical for maintenance of desert lakes in this temperate zone, especially during intervals when the mean annual rainfall is more than 100 mm.

Rapid shifts between sand seas and lakes in geologically and environmentally diverse settings suggest that the drylands of China are very sensitive ephemeral systems, and not long-lasting as previously thought. Available chronologies suggest that there were large lakes in the western Taklamakan Desert and the Chadamu Basin during MIS (Marine Isotope Stage) 3, at ~30 ka, probably related to a period of strong influence of northern hemispheric westerly winds. Channels and elevation models revealed by SRTM data and remains of lacustrine sediments also indicate that there was a large lake in the Hunshandake Sandy Lands in the eastern portion of the desert belt during the Quaternary.

There is significant evidence that during the middle Holocene strong summer monsoons led to a relatively large increase in moisture availability in the entire desert belt of northern China. Lacustrine records from the Badain Jaran Desert in western Inner Mongolia suggest that it was generally dry before 10 cal ka, becoming wetter from 10 to 4 cal ka, and dry again afterwards. Study of palaeosols widely occurring in dune stratigraphy in the eastern portion of the desert belt, suggests that there was a period of wet and warm climate in this region during the mid-Holocene Optimum, at a minimum between 6 ka and 4 ka, but possibly lasting longer.

Recent observations dealing with the generation and transport of dust from Central Asia indicate that the causal relationship between sand seas and loess sequences is not as close as previously assumed. These results suggest that there is an urgent need to examine whether the frequency and amplitude of climatic variation in Chinese deserts are somehow similar to that having occurred in the Sahara Desert of North Africa.

Deserts in northern China were also important focal regions for Neolithic cultures during intervals when environmental conditions supported a denser vegetative cover. There is evidence that some areas of woody vegetation to the west of Badain Jaran Desert were deforested by humans by ca. 4000 yr B P, although it is still debatable whether humans have had a significant impact in other areas at that time. Opinions on the severity of desertification vary and are sometimes contradictory due to the lack of long-term, field-based, investigations.

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1. Introduction

The term dryland, which includes both arid and semi-arid areas, refers to both climate and landscape. In Köppen's (1931) classification, these arid and semi-arid climates belong to BWk and BSk climate regimes, respectively. A different climate classification and indexing system based on the relationship between temperature and precipitation has been widely used in Chinese science communities. The aridity index, K is defined by:

$$k = \frac{0.16\sum t}{r}$$

where $\sum t$ is the annual sum of all daily mean temperature $\geq 10\ ^\circ C$, r is the precipitation (mm) over the same period, and 0.16 is an empirical constant (CAS, 1959).

"Arid" regions are classified as areas where K is $\geq$4.00, and semi-arid regions as areas where $1.50 \leq K \leq 3.99$. According to these criteria, the boundary between arid and semi-arid regions in China occurs at the north-south trending Helan Mountains ($\sim$106° E) (e.g., Ren, 1980; Zhu et al., 1980; Fig. 1).

Arid and semi-arid areas account for one third of the Chinese landmass and are found over elevations ranging from 155 m below sea level in the Turpan Depression to over 5000 m above sea level (a.s.l.) in intramontane basins on the western Tibetan Plateau (Zhu et al., 1980; Derbyshire and Goudie, 1997). Vegetation types in these drylands are diverse and include true desert (Goudie, 2002), desert steppe, steppe and scrub-woodland environments. In Chinese publications deserts were described primarily, however, as fields of active dunes (e.g., Zhu et al., 1980) with emphasis on the landforms of these deserts rather than the climatic conditions that form them.

Many areas in the mid-latitudes of the Northern Hemisphere experience humid climate conditions and are fertile agricultural regions, usually under the impact of westerlies. In contrast, although located at the mid-latitudes, a large portion of northern China is dryland since it is far from the westerly moisture source, i.e., the Atlantic Ocean. This zone is more intensely influenced by the dry and cold winter monsoon originating from the Mongolian-Siberian High Pressure centre than by moisture-carrying summer monsoons from the Pacific or Indian Oceans related to the East Asian monsoon system (e.g., Ren, 1980; An et al., 2000; Yang et al., 2004). Three different climate systems, i.e., the East Asian monsoon, Indian Ocean monsoon and Northern Hemisphere westerlies, have an impact on the climate of the drylands in northern China (e.g., Yang and Scuderi, 2010). Consequently, improved knowledge of how climate does change in these dryland areas offers clues that allow us to decipher the changes in these different systems. Although aridity is primarily responsible for the harsh conditions in these drylands, cold fronts that produce low temperatures and heavy snowfalls are also an important factor.

Like other drylands worldwide (e.g., Goudie, 2002; Tooth, 2009), investigation of the timing and nature of environmental change in arid and semi-arid regions of China remains a challenging task. The availability of relatively few high-resolution records coupled with the infrequent preservation of biotic remains in open-air dryland sites, the result of low primary production, generally oxygen-rich conditions, and a lack of long-lasting, anoxic lakes and swamps, lead to significant uncertainty in both the dating and interpretation of proxy records. While significant geomorphological evidence of climate change occurs in the drylands, it often only provides low-temporal resolution and site-specific information.

Knowledge of the nature and impact of Quaternary and Holocene climate change over a large portion of the deserts of China would remain just speculative without in-depth research directly in the dryland areas. However, due to the lack of continuous well-dated records from Chinese drylands, derived palaeoenvironmental data are not currently able to show the full history, spatial extent and impact of Quaternary climatic changes. Thus, interpretation of climate variability from deserts must be confirmed by other records such as ice-cores from surrounding mountain ranges. Reconstruction of synoptic palaeoclimatology, however, is possible if available records are combined and jointly interpreted and, in some cases, reinterpreted in the light of newer analyses.

For example, the Dunde ice core record from the northeastern Tibetan Plateau, between deserts in the Chaidamu Basin and the Badain Jaran Desert, was originally reported to be at least 100,000 years long (Thompson et al., 1989). A sudden increase in dust concentration and a change in oxygen isotope values, 14 m from the bottom of the Dunde ice core, was attributed to the glacial-stage colder climates, with the Pleistocene late glacial-stage interpreted as colder, wetter, and dustier than 'Holocene' conditions. Recently, several ice core records from the Tibetan Plateau, originally dated to the Pleistocene, have now been shown to be Holocene in age (Thompson et al., 2005). AMS ^{14}C dating of plant remains from nearly the bottom of these cores now suggests that these glaciers may have developed since ca. 6000 cal yr B P (Thompson et al., 2005). Climatic conditions, originally interpreted from these cores as multiple Quaternary glacial advances, actually took place during the mid to late Holocene, since the entire record is now believed to

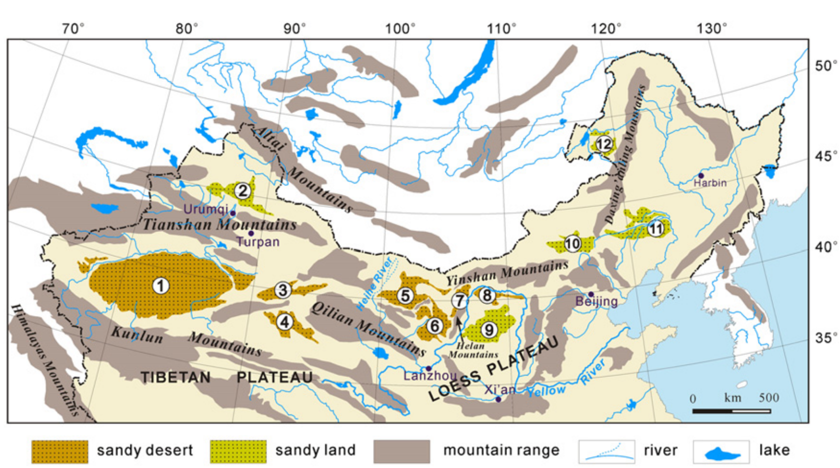

Fig. 1. Overview of the landscapes in northern China. Sandy deserts (active dune fields) and sandy lands (fields of stabilized dunes) are indicated with numbers. 1, Taklamakan; 2, Gurbantunggut; 3, Kumtag; 4, Chaidamu; 5, Badain Jaran; 6, Tengger; 7, Wulanbuhe; 8, Kubuqi; 9, Maowusu; 10, Hunshandake; 11, Horqin; 12, Hulunbeier (modified from Yang et al., 2011).

be ~6000 years long. This suggests that climatic instability in the region is much more profound than previously assumed. In the last 60 years conditions have been as warm as 6000–8000 years ago, the warmest temperatures in the entire record (Thompson et al., 1989). This adds an additional perspective to the study of change in China's deserts and demonstrates that research directly in deserts, if we are really interested in knowing what happened in these extensive areas, requires a special system with specific research approaches.

Over the last two decades, the increased number and quality of studies have improved our conceptual understanding and reconstructions of environmental changes in drylands. In what follows we aim to investigate the histories and potential mechanisms of Quaternary environmental changes in the dryland regions of China by examining available studies and noting important research questions that highlight significant research gaps and identifies urgently needed future work.

2. Modern processes and new considerations for interpreting geological records

Results from recent studies of climatic and geomorphologic processes in drylands raise questions and reservations about our earlier interpretation of these palaeoarchives for environmental reconstruction. Three important aspects, i.e., evaporation estimates, the control of dust (loess) generation and transport processes, and dune activity in deserts, are worthy of particular attention.

2.1. Revision of the water balance in dryland environments

Water is the most critical limiting factor in the dryland environment, and, since most of the arid and semi-arid regions of China are contained within endorheic drainages, specific understanding of the water balance, especially as related evaporation, are of great importance. The most authoritative early monograph about Chinese deserts (Zhu et al., 1980) notes that mean annual evaporation is between ~1400 and 3000 mm/yr in desert environments, and between 3000 and 3800 mm/yr in dune fields.

While these estimates have been widely accepted (e.g., Chen et al., 2004) they are questionable because they were derived from measurements using evaporation gauges with a diameter of 20 cm placed 70 cm above ground level. This spatial arrangement fails to capture the effect of reduced wind velocity near the surface and biases the results towards higher evaporation values. In addition, the results are compromised by differences in vapour pressure above open water relative to the gauge (vapour pressure is higher above the lake than above the smaller gauge) and heat conduction from the evaporation gauge (the use of unshielded metal enclosures results in heating of the gauge and the water within). These gauge characteristics produce excessively high evaporation values relative to actual conditions.

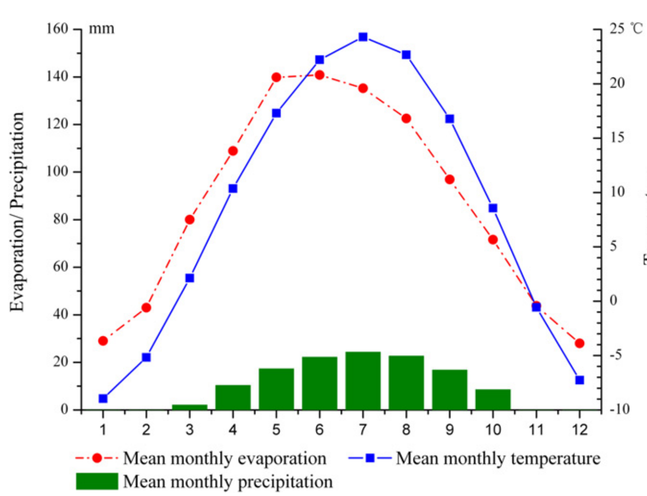

Fig. 2. Revised estimates of mean monthly evaporation from fresh water surface in the Badain Jaran Desert, with a mean annual sum of 1040 mm. The mean annual precipitation in the site reaches 105 mm (modified from Yang et al., 2010).

Using hydrological simulations and data from field observations with newer standardized techniques, Yang et al. (2010) re-estimated the actual evaporation in the Badain Jaran Desert and concluded that mean annual evaporation is only ~1000 mm/yr from water surfaces (Fig. 2) and ~100 mm/yr from dune surfaces. Yang et al. (2010) argued that these lower numbers are much more realistic, because they are similar to the few available data points measured using standard 20 m^2 evaporation pools. There is no doubt that the boundary conditions of the evaporation pools, and the values from the new approach at approximately one third of previous estimates, are much closer to that of natural water bodies than those of evaporation gauges traditionally used in China.

These revised evaporation estimates, suggesting that the loss of water in drylands is not as large as previously thought (e.g., Chen et al., 2004), require a new assessment of the local and regional water balance in drylands - one that has significant implications for reconstruction and interpretation of past environmental change. For instance, in the Badain Jaran Desert, it now appears that lake levels can be maintained in areas where mean annual rainfall exceeds 100 mm, provided that other geographical parameters remain the same as today (Yang et al., 2010). Previous studies, using much higher estimates of evaporation rates from desert regions that produce expected evaporative losses much larger than we have observed, suggested that the survival of lakes within the Badain Jaran was impossible without an additional water supply. Under this assumption of higher total annual evaporation, Chen et al. (2004) suggested that there must be significant groundwater flow from the mountainous region in the northeastern Tibetan Plateau to the Badain Jaran Desert to maintain these lakes. However, the geology and hydrology of the region precludes such a source, and in concert with the revised evaporation estimates, distant groundwater sources are not required to support the lake system.

2.2. Dust (loess) generation and sediment transport processes

Sun (2004) used the fine fraction of loess as a proxy for intensity and pathway shifts of the high-level westerly circulation over China. However, observation of modern dust storm deposits shows that fine grain size is not necessarily related to high-level transportation processes because fine particles can form aggregates or adhere to larger grains during dust storms (Qiang et al., 2010a). Some effort has been made to determine the earliest possible time of dust emission from the deserts, because this tipping point is believed to be consistent with the earliest occurrence of deserts in China. However, the question of how the sediments were originally brought into the deserts, and their sources, is still largely unanswered.

Recently, remote sensing analysis of a large number of modern continental sedimentary basins from various climatic and tectonic settings globally has shown that sedimentation in the majority of these basins is dominated by large fan-like landforms termed Distributive Fluvial Systems (DFS) (Weissmann et al., 2010). It has been suggested that DFS deposits represent the majority of the alluvial sediments in the rock record, and some of the deserts of China appear to be inactive DFS now buried by dunes. The DFS perspective, if correct, requires revision of earlier assumptions about alluvial deposition that interpreted alluvial deposits as being derived primarily from axial drainage systems or channel deposits.

2.3. Factors impacting our understanding of desert systems

2.3.1. Dune stratigraphy and winds

Generally speaking, the formation of sand seas is a response to arid climates, with the occurrence of sandy layers in sedimentary sequences from both deserts (Zhu et al., 1980) and desert-loess margins (Liu, 1985) commonly used as a proxy for changes in aridity. A crucial factor related to aeolian sand availability and its transport is the mobility of dunes. Case studies have shown that a number of parameters may be critical to the mobility and/or stability of aeolian features, but in general dune mobility is proportional to wind velocity, and inversely proportional to the ratio of precipitation to potential evapotranspiration (Lancaster, 1988). In most studies of palaeoenvironmental conditions, variability in wind velocity is not well documented. Because of these missing observations, interpretation of aeolian stratigraphy is often focused on measures of aridity or the ratio of precipitation to potential evapotranspiration (e.g., Muhs and Holliday, 1995; Yang et al., 2004; Fitzsimmons et al., 2007; Forman et al., 2008), even though the response of dunes to these climate parameters is not necessarily straightforward.

2.3.2. Soil formation and dune stabilization

Studies in semi-arid areas of the Great Plains and the southwestern deserts of the United States (Ellwein et al., 2011; Werner et al., 2011) show that soil-geomorphic features are fundamentally related to dune activity, with older aeolian surfaces more resistant to reactivation due to the presence of fine soil particles that increase over time in response to pedogenic processes. As a consequence of this age related process, younger aeolian landforms are more easily reactivated because of the lack of fine materials and significant soil formation (Ellwein et al., 2011; Werner et al., 2011). While difficult to recognize in cross-sections, Ellwein et al. (2011) have shown that this is an important, and often forgotten element in the understanding of dune mobility.

Climatic interpretation of dunes also suffers from non-uniqueness, because each aeolian section reflects only that dune's particular history with many factors impacting what is preserved. Besides, some types of dunes, such as the linear ones under bi-directional wind influence, are intrinsically inefficient at preserving complete records of their depositional history (Munyikwa, 2005). The occurrence of active dunes in desert regions is not necessarily related to decreases in moisture, either, but may be influenced by increase in wind strength (Bowers, 1982). Observations from inland dune areas of North America (Bowers, 1982) and recent re-interpretation of the grain size distribution in the loess-palaeosol sequence (Qin et al., 2005) from the Chinese Loess Plateau suggest that the occurrence of sand dunes in the desert and the coarsening of loess may be caused by an increase in wind strength during colder epochs rather than climate change related to precipitation. As such, interpretations based solely on moisture variability are suspect.

2.3.3. Complications introduced by local variability

The great variation in geologic and geomorphologic settings in the arid and semi-arid regions of China, as well as local variability in preservation of deposits, complicates our understanding of the larger scale synoptic picture of Quaternary climate change and its impact on Chinese deserts. While we expect that much of the uncertainty in the interpretation of the palaeoclimatic record from Chinese deserts, and much of the ensuing debate, is due to this local variability, each case needs to be investigated individually relative to the larger picture of regional geology and climatology in order to assess the impact of local influences.

While no such assessment of local variability exists for China, a recent study from the southwest United States illustrates the profound effects of local variability on the interpretation of lake level records (Scuderi et al., 2010). High-resolution monitoring of two desert basins in western North America showed that playa lakes separated by as little as 200 km can have input systems that respond to different regional climatic forcing, with the more northerly Animas/Lordsburg Basin showing a marked lake level increase in response to winter precipitation events, while the more southerly Palomas Lake Basin shows a stronger response to monsoonal and El Niño events (Scuderi et al., 2010). Thus, detailed knowledge about modern analogues in each system is crucial to the interpretation of palaeoenvironmental records. This finding suggests that some of the disagreement in the interpretation of Chinese records may be the result of under-appreciated local variability.

3. Initiation of dry climates in the middle-latitudes of Asia

3.1. The causes of aridity

The timing of the initiation of aridity in the Asian mid-latitudes and the causal mechanisms that produced it are closely linked. In eastern Asia, mountain ranges block moisture-carrying airflow from the west and south (the Pamir and Himalaya Mountains respectively). As well, the relative isolation of Chinese deserts from oceanic moisture sources significantly reduces the possibility of moisture penetrating to the latitude of Chinese deserts. The large barrier formed by the Tibetan Plateau retards and deflects the westerlies into northern and southern flows. Both flows then appear as an asymmetric dipole with convergence on the plateau's eastern side, with a large anticyclonic gyre to the north. This enhances cold outbreak northerlies, making East Asia colder than other parts of Asia at the same latitude (Wu et al., 2007).

Early numerical modelling suggested that the uplift of the Tibetan Plateau was the primary cause of the formation of the Mongolia-Siberian High (Manabe and Terpstra, 1974) and fundamental in producing the arid climates of China and Central Asia. From the perspective of thermal forcing, the Tibetan Plateau enhances aridity in central Asia, with summer heating producing a shallow cyclonic circulation near the surface and an anticyclonic circulation aloft with rising air on the eastern side of the plateau and sinking air in the west. Furthermore, Wu et al. (2007) have shown over mid-latitude mountain ranges of central Asia, that rising air predominates over central and eastern ranges, whereas sinking air is observed over the western ranges.

The role of the Tibetan Plateau in producing the arid climates of Central Asia is, however, not without debate because other factors, such as ice volume in Arctic regions, may modulate the intensity of aridity. Significant extension of Arctic ice causes the development of enhanced high pressure in north Asia, resulting in a stronger influence from the dry winter monsoon (Ruddiman and Kutzbach, 1989). Dupont-Nivet et al. (2007) argued that the initial establishment of aridity in Central Asia arose from global climate change at the Eocene–Oligocene transition as the Earth underwent a change from 'greenhouse' to 'icehouse' conditions, rather than from regional tectonism. Their evidence, derived from magnetostratigraphy and cyclostratigraphy of sedimentary sections from the Xining Basin on the northeastern margin of the Tibetan Plateau, indicates that the onset of drying occurred at the same time as the early Oligocene glaciation of Antarctica. Zhang et al. (2001) suggest that global climate change was the main driver for the change in sedimentation rate and grain size in northwestern China between 2 and 4 Ma.

Until recently knowledge of the climatic history of dryland China was derived primarily from interpretation of loess-palaeosol records from the semi-arid Chinese Loess Plateau. The occurrence of loess on most landforms including mountain ridges, and the preservation of land snails and plant remains in the loess, led Richthofen (1877) to attribute loess in China to aeolian processes. The gradual change in grain size on the Plateau also suggested that loess in China was sourced from the deserts located to the northwest (Liu, 1985). The initial establishment of a magnetostratigraphic chronology of the loess deposits in the Loess Plateau (Heller and Liu, 1982) enabled loess-palaeosol sequences to be used as important records for deciphering climate change in east Asian deserts.

Recent progress and debate over the palaeoclimatic interpretation of loess-palaeosol sequences (e.g., Stevens et al., 2006; Jiang F. et al., 2007; Hao et al., 2010) indicate that on-site evidence from drylands cannot be neglected. Classic theory relating high loess sedimentation rates to periods of intensified winter monsoon circulation and drier conditions has been challenged by results from modern observations (Roe, 2009). In the simplest interpretation of these records, loess is assumed to be derived from deserts and transported by northwesterly winds triggered by the Siberian-Mongolian high pressure system. Consequently, loess records have been applied to decipher the formation and variability of Asian monsoon systems (e.g., Ding et al., 2005).

Recent analysis shows that dust outbreaks in Asia occur predominantly in springtime, with dust-producing windstorms actually associated with cyclogenesis related to the breakdown of the Siberian High (Roe, 2009). Cyclogenesis in the lee of Mongolian Altai and strong meridional temperature gradients were found to be the key meteorological forcings required to create the dust storms that are the main agents of loess deposition. Roe (2009) speculated that the onset of winter sea ice during the Miocene might play a role in the onset of Asian dust generation, transport, and deposition, because increased sea ice in the Barents Sea causes enhanced springtime temperature variability over Central Asia. This new interpretation suggests that enhanced dust flux should be viewed as being the result of prolonged spring conditions rather than of more intense winter circulation (Roe, 2009).

The occurrence of loess is usually interpreted as an indicator of dry and cold conditions at both the deposition site and desert source areas (Liu, 1985). However, the nature of loess, as recent numerical simulations have suggested (Qin et al., 2005), may not be determined by environmental conditions (wet or dry) in the source areas, but rather by aerodynamic forcing related to vertical wind and turbulence during dust entrainment in the source area and turbulence intensity at the depositional site. Simulations indicate that the grain size change in loess-palaeosol sequences is primarily indicative of the aerodynamic nature of surface winds, with millennial length periods of strong turbulence corresponding with global cooling events and periods of weak turbulence corresponding with warm periods.

Recent research on the source of loess found in a variety of depositional settings indicates that not every loess section in northwest China can be used to deduce desert environmental history. Derbyshire et al. (1998) and Yang (2001) argued that the primary status accorded dune fields as the primary source of the loess on the Chinese Loess Plateau should be reassessed in the light of potentially significant inputs from piedmont alluvial fans and other dryland sources such as DFS (Weissmann et al., 2010). For example, loess from both the Mangshan (Jiang F. et al., 2007) and Zhengzhou Sequences (Huang et al., 2009) on the southern margin of the Loess Plateau was found to be partially derived from fluvial sediments of the Yellow River, with grain size change in these two sequences appearing to be closely related to course changes of the Yellow River (Jiang F. et al., 2007; Huang et al., 2009). Similar causative processes were found for the Xiashu Loess deposits whose primary source now appears to be from the flood plains of the Yangtze River instead of the deserts of northwest China (Hao et al., 2010). An increase in the grain size of loess in the Zhengzhou Sequence during the last 3100 years was recently attributed to human activity as well as climate change induced aridity on the flood plains of the Yellow River (Huang et al., 2009). These results and new interpretations about the sources (e.g., Stevens et al., 2010) and grain size characteristics of loess indicate that loess accumulation is much more complex than traditionally assumed.

3.2. The initiation of increased aridity

There are two significant questions associated with the initiation of arid climates in northern China. The first deals with the causal mechanisms that produced drier conditions in this vast region and specifically calls into understanding our knowledge of global climate change, tectonics, and the possible interplay between the two. The second addresses the timing of this change and focuses on whether, and to what degree, climate variability documented in the subtropics has influenced the deserts of China. To date most studies have focused on the first question, although we believe that the second question is more critical to understanding the development of the modern desert environment.

The timing of the initiation of desert conditions in China is controversial and has been debated for many years. Estimates for the uplift of the Tibetan Plateau range from the Pliocene (2–4 Ma) to the early Cenozoic (Tooth, 2008), with younger ages primarily based on tectonic-geomorphic evidence (e.g., Li, 1991; Shi et al., 1998) and Ar–Ar dating results that constrain valley formation in the headland areas of the Keriya River on the northern slope of the Kunlun Mountains (Zhao et al., 2008). Zhao et al. (2008) reported that the incision of the Keriya River was coincident with tectonic uplift along the northern margin of the Tibetan Plateau and aeolian sedimentation in the Tarim Basin at ca. 1.1 Ma. Shi et al. (1998) suggested that the formation of the presently high Tibetan Plateau began at ca. 3.4 Ma, and that the plateau was at an elevation of no more than 2000 m a.s.l. initially, with its surface eroded to <1000 m a.s.l. prior to the last uplift. A much higher and longer-lasting aeolian dust flux began at 3.6 Ma in the North Pacific, and has been attributed to the uplifting of the Tibetan Plateau and the onset of the northern hemisphere ice sheets (Rea et al., 1998).

Approaches using stratigraphic correlation between various records have been very useful in establishing a global palaeoclimatic perspective. The reliability of records from Chinese deserts might be confirmed if they are shown to be consistent with trends in the marine oxygen isotope record (Shackleton and Opdyke, 1973) and other well-researched proxies for climate over the Quaternary (e.g., Tan, 2009). However, uncritical comparison with these excellent records could lead to questionable results, much as the earlier model of four Quaternary glaciations constrained earlier palaeoclimatologists (Murray-Wallace, 2011). One example worthy of mention in the context of understanding climate change in drylands, is the different interpretation of sediment type on the western Chinese Loess Plateau. Sedimentological studies by Alonso-Zarza et al. (2009) suggested that most sediments in the Tianshui Basin (located between Lanzhou and Xi'an, Fig. 1) in the southeast are of alluvial and lacustrine origin rather than aeolian. These fine red clastic sediments, usually interpreted as aeolian red clays, are now interpreted as typical distal fan/dry mudflat areas, with light-coloured marl-like layers. While Alonso-Zarza et al. (2009) divided the sediments in the Tianshui Basin into four main stratigraphic units, their work dealt primarily with Unit II in the central portion of the basin. The presence of ooids and reworked calcretes in this unit indicates that cycles evidenced in the changing facies were indicative of lake expansion and desiccation. They suggested that relatively minor changes in the water balance of the basin could cause drastic facies variability, from lacustrine to mudflat, across wide areas due to the flat topography of the basin. In addition, the results bring into question the aeolian origin of late Miocene deposits in this region (Alonso-Zarza et al., 2009; Guo et al., 2010).

4. Deserts in China during the Pleistocene

On glacial-interglacial time scales, drylands are regions where some of the most spectacular changes of environmental conditions have taken place, with significant shifts between large lakes and bare dune-covered landscapes. In low latitudes, sand dunes of glacial periods are often widespread in areas that are now covered by forest or savanna vegetation with annual rainfall of 750–1500 mm (Goudie, 2002). Although evidence of similar large amplitude change is absent from drylands in the middle-latitudes, there is a variety of records indicating the extent of change in environmental conditions in China's drylands during the late Quaternary.

4.1. West and central regions

The Taklamakan Sand Sea represents the largest extension of hyper-aridity in northern China and generally across the Asian mid-latitudes. This large inland basin is surrounded by mountain ranges and is so isolated that few scientists visited the region until relatively recently. A continuous trend of aridification was first proposed for this region by Berg (1907), and recently derived geomorphologic evidence from these drylands suggests that large-scale fluctuations took place during the late Pleistocene. Alluvial and fluvial gravels and coarse sands underlie the Taklamakan Sand Sea and suggest that the geomorphologic processes that formed alluvial fans and fluvial deltas were active during the Quaternary (Zhu et al., 1981). Six cores from the southwest portion of the Taklamakan consist of fluvial deposits intercalated with aeolian sands, while a 300 m core from a water well in the western portion of the basin consists primarily of fluvial sands and silt (Li and Zhao, 1964). Knowledge of the sediment distribution in the interior of the basin from a larger number of cores and from greater depth would be useful for understanding the history of this desert.

Norin (1932) reported lacustrine sediments along rivers flowing into the Taklamakan Desert on the western margin of the basin, and wave-produced erosional forms and lacustrine sediments on the southern slope of the Mazhatage Mountains in the southwest portion of the basin. He suggested that a fresh water lake was present in the interior of the Taklamakan during the Quaternary. A larger early-Pleistocene lake, with a level as high as 1250 m a.s.l., was proposed by Shumef (original in Russian, cited in Zhu et al., 1981). The Lop Nuer is considered to be a remnant of this formerly extensive lake with dunes thought to have developed along the old lake shoreline.

Dunes now occupy over 80 percent of the basin, making a precise reconstruction of the earlier lake extension in the Taklamakan difficult. Due to deflation, lacustrine deposits are poorly preserved in the basin, however, some lacustrine sediments are preserved in bedrock outcrops in the sand sea (Fig. 3). Some of these deposits were recently OSL (Optically Stimulated Luminescence) dated (Yang et al., 2006) and show that multiple lacustrine sediments in the centre of the Taklamakan, between 1100 and 1150 m a.s.l., date to ca. 30,000 (another dates to between ca. 30,000 and 40,000 with large uncertainty). In the southern part of the sand sea, an outcrop of lacustrine sediments at 1250 m a.s.l. was dated to ca. 3 ka (Fig. 3). Using SRTM data, we reconstructed lake extents at altitudes ranging from 1100 to 1150 m a.s.l. (Fig. 4). Based on our depositional ages, the 1100 m a.s.l. lake level represents the landscape in the Taklamakan Desert at ca. 30 ka (Fig. 4). Additional fieldwork is required to confirm whether such a large lake existed in this basin at that time. If the reconstruction is correct, the high lake level suggests a significantly increased water supply resulting from a period of either significantly wetter climate or a higher precipitation/evaporation ratio. Since the basin would be nearly filled with a lake at 1200 m a.s.l., Shumef's reconstruction would suggest even wetter climatic conditions sometime earlier in the Pleistocene.

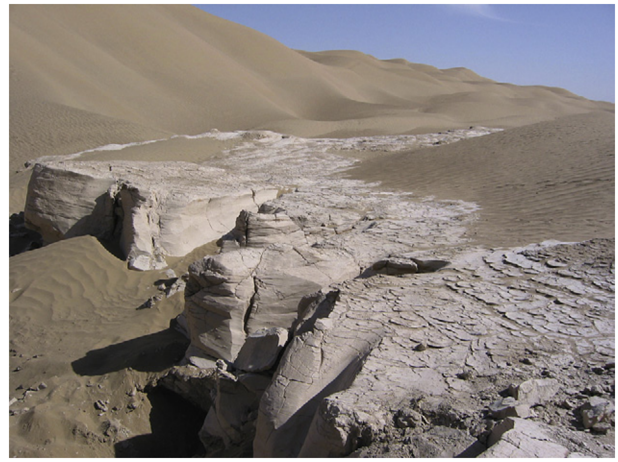

Fig. 3. Outcrops of the lacustrine sediments in the central Taklamakan. The remains of former lacustrine sediments (1 m in thickness, the aeolian sand beneath was dated to 2790 ± 240 yr by OSL; Yang et al., 2006) are white and cemented, buried by the dunes reaching 30 m in the left side of the photo.

The largest environmental variation that we are aware of during the late Pleistocene probably occurred in the Chaidamu Basin. The basin, currently filled with halite deposits and yardangs, was initially filled with a large fresh water lake (Fig. 5). Based on the interpretation of satellite imagery, shoreline mapping and radiocarbon dates from a sedimentary core, Hövermann and Süssenberger (1986) suggested that an early Chaidamu Mega-Lake was ca. 400 m deep at ∼30 ka, with the lake level decreasing continuously during the last 30,000 years. Calculating the clastic sedimentation rate, Hövermann (1998) concluded that mean annual precipitation in the catchment of the former lake fluctuated greatly from ca. 350 mm at 25 ka to just 30 mm at present (Fig. 6). Broadly consistent with Hövermann and Süssenberger's (1986) interpretation, Chen and Bowler (1986) found that climate was relatively humid and the lakes remained fresh to slightly saline in the Chaidamu Basin from before 40 ka to about 25 ka. Chen and Bowler (1986) suggested that the climate became progressively drier and the lakes entered a phase of evaporite concentration after 25 ka. Hövermann (1998) also suggested multiple cycles of change, with five periods of higher mean annual precipitation occurring during the last 25 ka, with mean annual precipitation of such wetter periods decreasing continuously to the present (Fig. 6).

Yang et al. (2003) recognized multiple phases of dune formation in the Badain Jaran Desert, and suggested that surfaces delimited by calcareous cementation resulting from pedogenic processes were related to periods of increased precipitation. Four such older

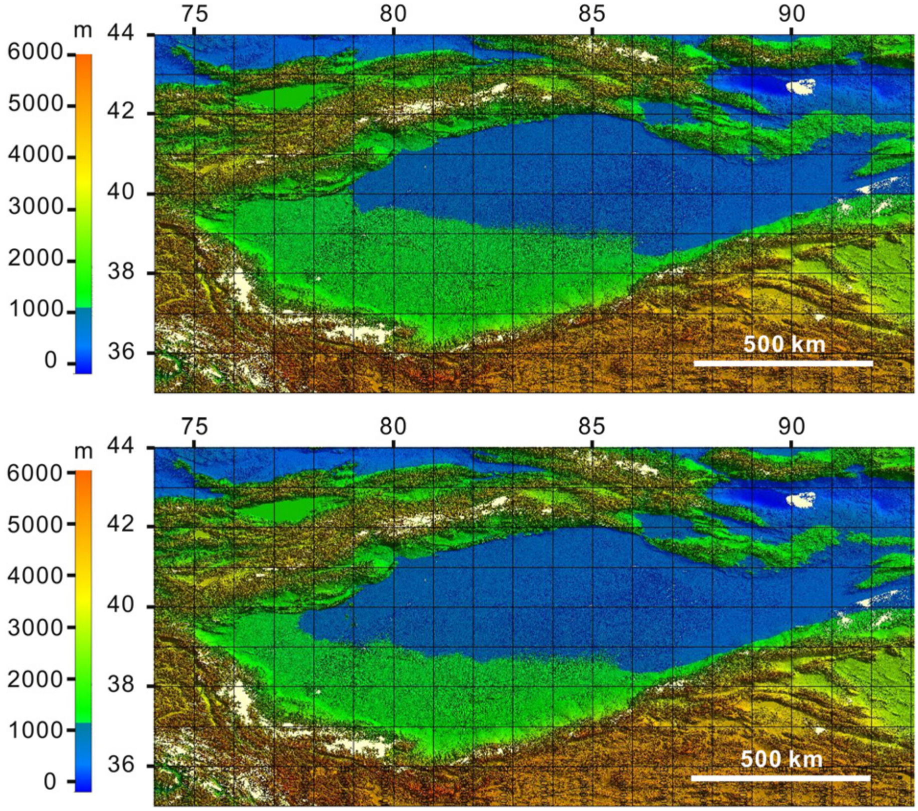

Fig. 4. Potential areas of the mega-lake (marked in blue) in the Taklamakan while water reaches the lake level of 1100 m a.s.l. (upper) and 1150 m a.s.l. (bottom), respectively. The water would be largely recharged by the rivers with headwaters in the surrounding mountains.

surfaces were radiocarbon dated indirectly by dating this calcareous layer (Fig. 6). In this context, the dunes are actually aggregations of dunes from different ages (Fig. 7), with sand surfaces related to different periods remaining distinguishable (Yang et al., 2003). Although this surface type is indicative of climate change, the precise duration of the surface cannot be established at this stage because of the uncertainties about hard-water effects on radiocarbon ages.

Fig. 5. Yardangs in the western Chaidamu Basin (the one with a person on the top is ca. 10 m high). The hilly remains of the lacustrine sediments (formed by deflation and called yardangs in geomorphology) mark the bottom of a mega-lake with its largest extension at around 30 ka.

OSL chronology from early shorelines around Qinghai Lake, located east of the Chaidamu Basin, shows that maximum highstands ∼20–66 m above present-day lake levels occurred during MIS 5 (ca. 130–75 ka), between ca. 100 and 90 ka (Madsen et al., 2008) and not in association with MIS 3 (ca. 60–28 ka), as found in the Chaidamu Basin. This high lake level during MIS 5 has not been exceeded in the basin since 90 ka, implying a more expansive Asian monsoon in MIS 5 (Madsen et al., 2008).

Palaeoshorelines and OSL chronology also suggest that there was a mega-lake in the eastern Wulanbuhe Desert and north of the Kubuqi Desert before 60–50 ka. This lake decreased in size until it totally disappeared in the early Holocene. Currently this former lake, estimated to be larger than the modern Lake Baikal (Chen et al., 2008), is characterized by salt mines. Since the Wulanbuhe and Kubuqi Deserts are located on the shore of this large former lake, it is quite likely that they are younger than 50 ka. Because this lake is in the drainage basin of the Yellow River, the climatic conditions that produced this mega-lake are not yet understood and we assume that it was a terminal lake of the Yellow River at that time.

While there is still a large number of lakes in the inter-dune basins of the Tengger Desert, remains of lacustrine sediments and palaeoshorelines indicate a more extensive occurrence of lakes and swamps in the past. Palaeobeaches around Baijian Lake in the Tengger Desert, investigated in detail with radiocarbon dating, show lake levels in continuous decline during the last 35,000 years (Pachur et al., 1995; Fig. 6). Qiang et al. (2010) used grain size change in loess-palaeosol sequences south of the Tengger Desert to decipher the change in surface wind strength in the deserts and suggest that surface winds were much stronger from 19.1 to 11.4 ka, gradually weakening after the beginning of the Holocene, reaching

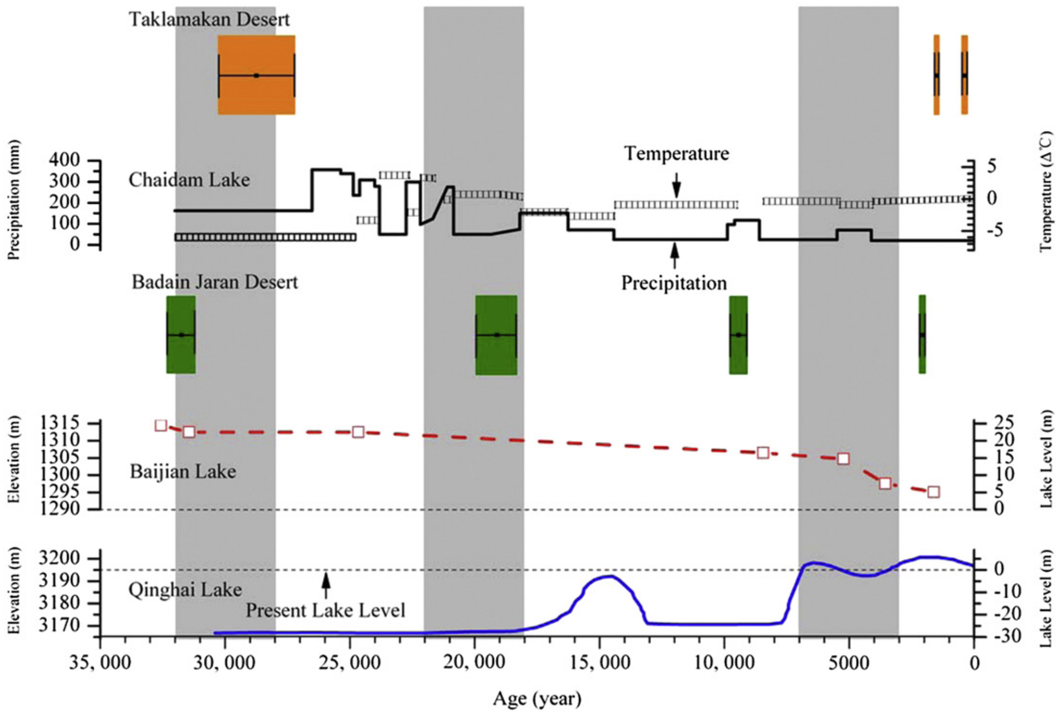

Fig. 6. Reconstruction of the palaeoclimatic changes in the deserts of China during the last 32 ka. The wetter events in Taklamakan were interpreted from lacustrine sediments in the dune field (Yang et al., 2006), those in Badain Jaran were from calcareous cementations in the dunes (Yang et al., 2003). Data about changes of lake levels in Qinghai Lake were from Madsen et al. (2008), those in Baijian Lake of Tengger Desert from Pachur et al. (1995). The changes of temperature (ΔT) and precipitation in the Chaidamu Basin were based on lacustrine sedimentation in the former lake of this basin (Hövermann, 1998).

a minimum between 4.0 and 3.5 ka and again experiencing an increase after 2.5 ka (Qiang et al., 2010).

Based on geomorphic evidence we conclude that climate in northwestern China was generally wetter during the interval from ~41 and 30 ka (Yang and Scuderi, 2010). Such variations could be caused by a change in summer monsoon penetration and the intensity of north hemispheric westerly winds (Yang and Scuderi, 2010). The development of dune fields cannot be completely understood until detailed knowledge of interactions between a range of geomorphic features and the dune fields has been obtained. Little is also known about why dune type and size vary greatly across the drylands of China and the forcing variables that cause these differences. Investigations of these relationships should be an urgent topic for future research. Outside of well-studied aeolian processes, other erosional and depositional processes in drylands that led to the formation of the modern desert landscape have been poorly studied. As an example of another process significantly impacting dune formation, Hövermann and Hövermann (1991) and Yang (1991) reported that moraines occurring on the southern margin of Taklamakan possibly were the direct source of some southern Taklamakan dune fields. The intense weathering of these moraines indicates, in the absence of radiometric dates, that they are not from the last glaciation but from earlier ones.

Fig. 7. Dunes of various generations in a single dune complex, with younger generations on the surface, and older generations building the bases. The younger generation of dunes appears secondary and consists mainly of smaller and simple forms while the old generation decides the primary size of the dunes. The lake in the middle is ca. 2 m deep (ca. 350 m in the longer axis) while the dunes reach a height of ca. 300 m.

4.2. Eastern portion

In contrast to the debate over climate variability in the arid regions of China, it is widely accepted that there was frequent Quaternary climate change in the semi-arid regions of China. Many aeolian sequences in eastern regions contain palaeosol layers that are indicative of a relatively dense vegetation cover and relatively warm and wet conditions. In the Hunshandake, results suggest that these palaeosols date from the Holocene Climate Optimum (Li et al., 2002; Yang et al., 2008). Initial analysis of lacustrine sediments is beginning to suggest the presence of a large lake, although a chronology of lacustrine sedimentation in the Hunshandake is not yet available.

Fig. 8 based on SRTM data, shows the lake extent at various elevations. On the top of a hill at an elevation of 1090 m we found white-coloured lacustrine sediments composed of fine silt and clay that suggest that they were deposited in relatively deep water (lack of any organic matters, our unpublished field data, 2010).

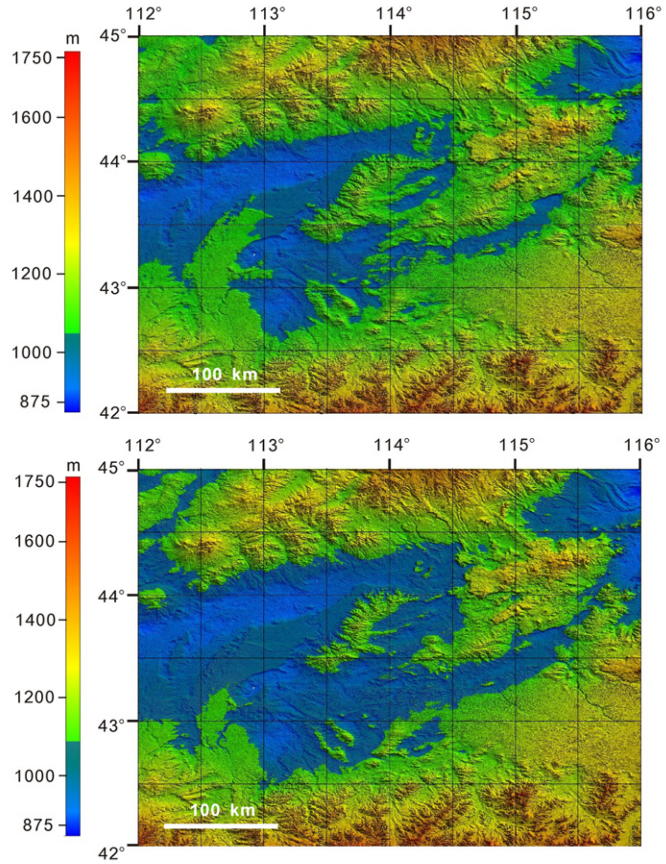

Fig. 8. Potential areas of the mega-lake (marked in blue) in the Hunshandake while water reaches the lake level of 1050 m a.s.l. (upper) and 1090 m a.s.l. (bottom), respectively. The water would be recharged by the rivers with headwaters in the surrounding mountains.

Although these lacustrine sediments are not yet dated, their unconsolidated nature and association with higher lake levels suggests that they are older than Holocene in age, and most likely formed during the late Pleistocene. At a lake level of 1090 m a.s.l., northern and northwestern sections of the Hunshandake would be covered by a large lake with some isolated island areas (Fig. 8). Even with lake levels between 1010 and 1050 m a.s.l., large portions of the Hunshandake would be inundated. Analysis of SRTM data reveals channel systems at the margins of the Hunshandake. The channels appear to be palaeodrainages that are possibly the remnants of an endorheic drainage system of inflow channels to this lake (Fig. 9).

Middle-latitude drylands in China may have experienced multiple cycles of change during the late Quaternary, much like other drylands globally. Palaeoshorelines and lacustrine sediments in California during the late Pleistocene, show that the southwestern United States desert experienced several periods with significantly expanded lake extents, even though all of these formerly large lakes are now largely dry basins (Wells et al., 2003). Analysis of dunes in the Strzelecki Desert of Australia also suggests that the production of aeolian landforms does not always occur in association with phases of pronounced aridity, with source-bordering dunes commonly formed during periods of enhanced river flow and sand supply (Cohen et al., 2010). In light of these findings, and because there currently is no systematic chronology of any of China's sand seas, more detailed studies of dune development in these vast areas are necessary to fully understand the climatic signals they contain.

5. Holocene changes of the deserts

5.1. West and central portions

Although a few recent reviews of Holocene climate change in northwestern China have been published (e.g., An et al., 2006; Chen et al., 2008a; Yang and Scuderi, 2010), it is apparent that there is still a great need to study these areas and expand our knowledge. Opinions on the Holocene climatic history of China's drylands vary considerably, in large part due to the fact that most lake, swamp and dried peat bog records used to produce dryland chronologies are primarily based on radiocarbon dating with significant hard-water effects. In lieu of an actual understanding of its impact on dating, in many studies the hard-water effect is assumed to be consistent throughout the lacustrine core and its value is determined by the radiocarbon age of the surface or near-surface sediments from the core.

However, the correct calculation of hard-water effects is a challenging task and miscalculation or non-application of a correction can lead to spurious dating or wide dating error bars. For example, in a swamp in the Horqin Sandy Land (Fig. 1) the hard-water effect was reported as ca. 2 ka (Ren, 1998), but only 1.14 ka at Lake Bosten on the northeastern margin of the Taklamakan Desert (Chen et al., 2006). In a lake in the central Tibetan Plateau, Wu et al. (2006) found that the hard-water effect could be as large as 3.47 ka. Dating calcareous palaeosols by radiocarbon is even more challenging due to a large and inconsistent hard-water effect. A disparity of a few thousand years occurs between dating results from inorganic carbonate and organic carbon in soils from eastern Inner Mongolia (Yin et al., 2005). This value is similar to the 0.5 to 7.0 ka variation seen in radiocarbon ages from inorganic carbonate in calcareous palaeosols and organic carbon from samples from the arid zone of Australia (Williams and Polach, 1971).

Due to the complexity of palaeoclimatic proxies and the possibility of non-uniqueness in their interpretation, Yang and Scuderi (2010) have previously pointed out that different conclusions may be drawn from different proxies in a same core. With that caveat in mind, we note that Holocene climate in the currently arid regions of China was likely characterized by a distinct increase in moisture availability during the middle Holocene.

The case of the Badain Jaran is worthy of particular attention in the context of reconstruction of Holocene climate change in deserts. A general picture of the Holocene climate history of the region emerges only after all the data are compiled. Although some earlier papers (see Yang and Scuderi, 2010 and the references therein) have reported dry conditions during the mid-Holocene in areas adjacent to the Badain Jaran Desert, more recent work and re-interpretations of earlier research suggest that it is highly likely that the entire Badain Jaran Desert region was wetter during the middle Holocene. The interpretation of the climate history in drylands is dependant on the assessment and re-evaluation of the radiocarbon dates because of the hard-water effect. Our re-examination of earlier data taking into account the value of the hard-water effect for all lacustrine records of the Badain Jaran (Dong et al., 1996; Hofmann, 1996, 1999; Hofmann and Geyh, 1998; Li et al., 1998, 2005; Yang, 2000, 2006; Yang and Williams, 2003; Yang et al., 2010), and incorporating site-based corrections for lacustrine records from other regions (Lister et al., 1991; Shi et al., 2002; Jiang et al., 2007; Hartmann and Wünnemann, 2009), leads to the establishment of the framework of the Holocene climate history in the region (Fig. 10). We applied the corrections produced by Hofmann and Geyh (1998) to produce an updated radiocarbon chronology for the Badain Jaran Desert (Hofmann, 1996; Hofmann and Geyh, 1998; Li et al., 1998; Yang, 2000, 2006; Yang and Williams, 2003; Yang et al., 2010). A careful study of the present-

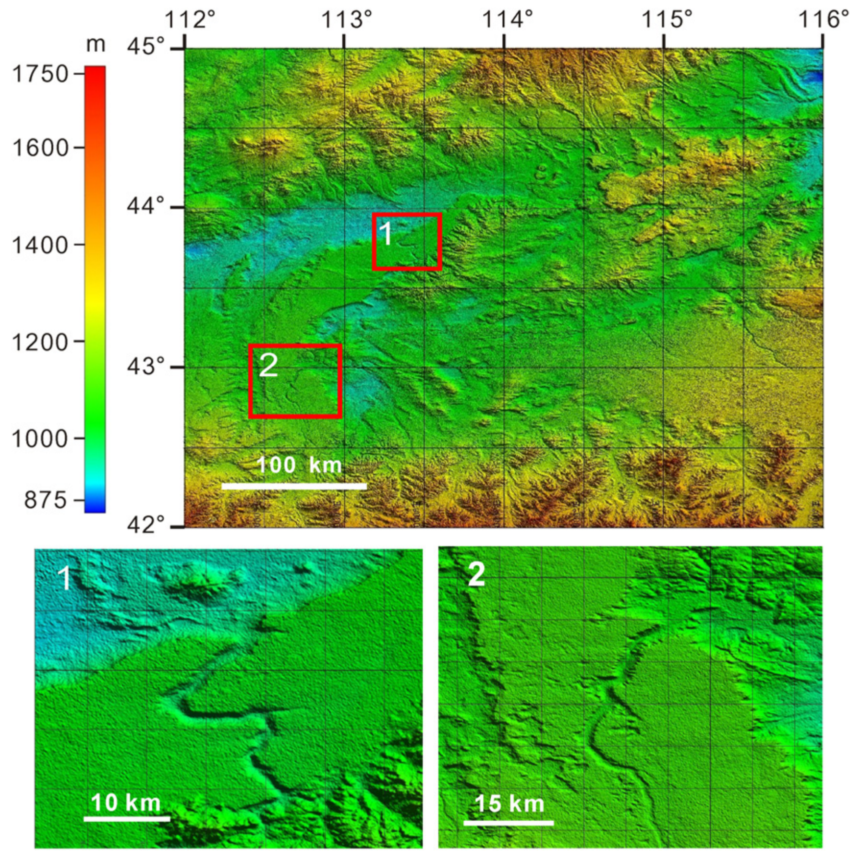

Fig. 9. Dried channels indicating inflows of the former mega-lake in the Hunshandake (data source: SRTM, http://dds.cr.usgs.gov/srtm/version2_1/SRTM3/Eurasia).

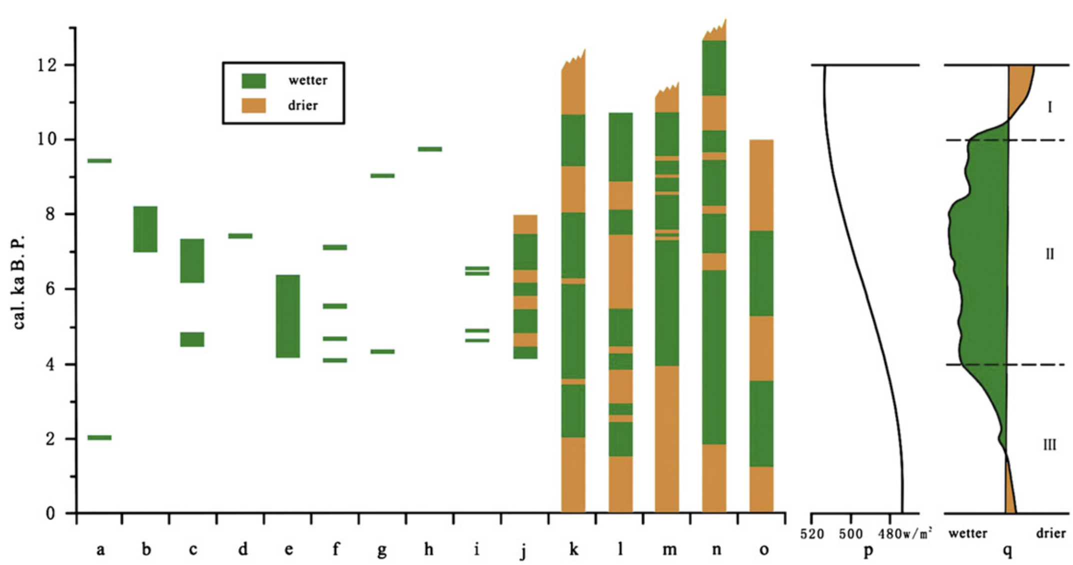

Fig. 10. Dry and wet epochs inferred from palaeoenvironmental records in the Badain Jaran Desert and compared with those from other dryland regions in China (a–o), and the general trend of the relative aridity changes (q) deciphered from the synthesis of these records, and compared with the Holocene changes of summer (May–September) solar insolation at 40 °N (p, Berger and Loutre, 1991). Origins of the data: a, calcareous cementations on the dune surface in the Badain Jaran (Yang, 2000); b – i, lacustrine sediments in the southeastern Badain Jaran (for locations of these lakes see Fig. 11); b, Huhejilin Lake (Yang and Williams, 2003); c, Zhalate Lake (Hofmann, 1996, 1999); d, Sumujilin Lake (Yang and Williams, 2003); e, Nuoertu Lake (Hofmann and Geyh, 1998; Yang and Williams, 2003); f, Shaobaijilang Lake (Yang et al., 2010); g, Aomenjilin Lake (Yang et al., 2010); h, Sayinwusu Lake (Yang et al., 2010); i, Badain Lake (Li et al., 1998; Yang et al., 2010). j, Shugui Lake in the eastern margin of Badain Jaran (Yang, 2006); k, aeolian sequence in the southern margin of Badain Jaran (Dong et al., 1996; Li et al., 2005); l, Juyanze, the terminal lake of the Heihe River (Fig. 1; Hartmann and Wünnemann, 2009); m, a terminal lake in the Tengger Desert (Shi et al., 2002); n, Qinghai Lake in the northeastern Tibetan Plateau (Lister et al., 1991); o, Wulungu Lake on the northern margin of Gurbantunggut (Jiang et al., 2007).

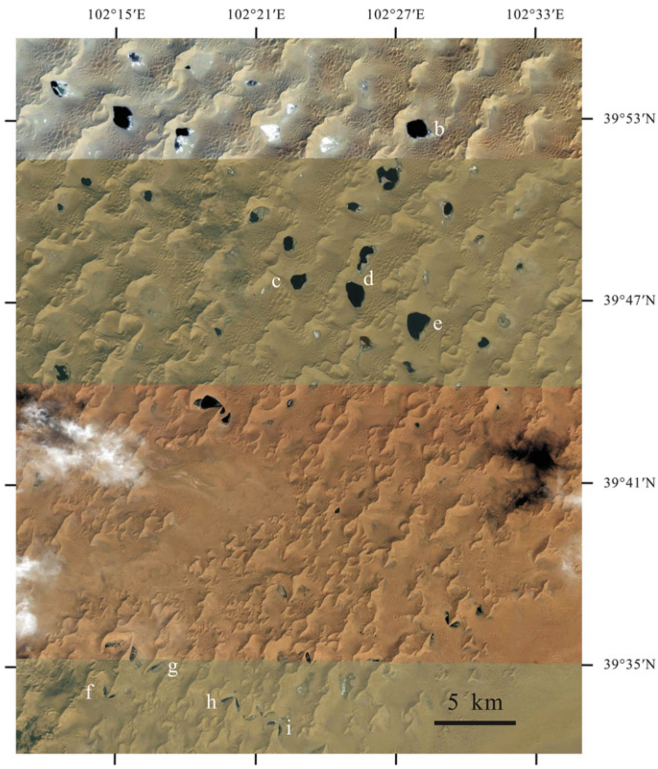

Fig. 11. Distribution of the lakes in the southeastern Badain Jaran (Letters mark locations of the lacustrine sequences shown in Fig. 10. Remote sensing data from Google Earth).

day and Holocene sediments suggests that the radiocarbon age reservoir effect is −3220 ± 225 yr for the inorganic fraction and −1080 ± 155 yr for the organic fraction in the lacustrine sediments of the Badain Jaran (Hofmann and Geyh, 1998). Fig. 10 shows the results of our re-interpretation after the corrections of the radiocarbon chronology, including assessments of nine lakes in the Badain Jaran Desert, an aeolian sequence from the south margin of the sand sea (Dong et al., 1996; Li et al., 2005; organic remains dated with no reservoir impact applied), indicators of pedogenic processes (Yang, 2000; calcareous cementation, with no hard-water effect reference available), the results from a new interpretation of sediments from the lake located north of the Badain Jaran (Hartmann and Wünnemann, 2009), and a lacustrine record in Tengger Desert (Shi et al., 2002) as well as the record from Lake Qinghai (Lister et al., 1991). The record from Lake Qinghai is corrected by −1.1 ka following a more recent study by Wang et al. (2010). All ages were calibrated online under CalPal Online (www.calpal-online.de, Table 1 in Supplementary material).

Fig. 10 indicates that the area was generally dry before 10 cal ka, became wetter at 10 ka (particularly after 8 ka), remained wet until 4 ka, and then dried afterwards to the present. Neither of the records shows evidence for an increase in moisture availability over the last two thousand years (Fig. 10). This pattern is similar to known Holocene variability in the East Asian summer monsoon, and suggests that Holocene precipitation in the Badain Jaran and other arid and semi-arid areas was controlled by this climatic forcing mechanism. A plausible explanation for these observations would be the emplacement of a stronger East Asian summer monsoon, possibly the result of higher early-to-mid Holocene insolation.

In more western regions like the northern margin of the Gurbantunggut, the wet period was probably of shorter duration, from 7.6 ka to 5.3 ka, according to pollen and ostracod records from Wulungu Lake (Jiang Q. et al., 2007). In the southeast portion of the Chaidamu Basin, proxy records indicate that it was wet between 6.5 and 4.7 ka, reflecting a mid-Holocene summer monsoon maximum. Further interpretation of high-resolution fossil pollen, peat, and sediment (loss-on-ignition) proxies, indicates that conditions became significantly drier between 4.7 and 2 ka with a drying trend that continues to the present (Zhao et al., 2011).

A new ice core chronology from the Tibetan Plateau (Thompson et al., 2005) confirms that climate in the drylands of China can change abruptly and dramatically. This moisture sensitive record indicates periods with enhanced precipitation, precluding the possibility of continuous aridification during the Holocene. However, most records from dryland regions and their margins show a late Holocene drying trend.

5.2. Eastern portion

Two shortcomings complicate the interpretation of proxy records and the reconstruction of a high-resolution palaeoclimatic history for the eastern region. First, the continuity of aeolian accumulation cannot be precisely assessed and commonly used chronological interpolation cannot, and should not, be applied to such records. Second, although lacustrine records are often used for palaeoclimatic studies, it is unclear whether some lakes experienced periods of complete desiccation during the Holocene.

Holocene climatic change in eastern China's semi-arid regions is characterized by the wide occurrence of kastanozem soils in dune stratigraphy in all of the sandy lands (Fig. 12). Most of these soils date to the middle Holocene although the ages are not fully consistent between various sections (see Yang and Scuderi, 2010 and references therein). It is quite likely that most dunes in these semi-arid regions were vegetated during the mid-Holocene, with active sand dunes probably rare at this time. Changes in species assemblages and shell chemistries of ostracodes in Hulun Lake in eastern Inner Mongolia show that the driest period in the Holocene was between 4.3 and 3.3 ka, with maximum warmth between 8.3 and 6.2 ka (Zhai et al., 2011).

A synthesis of available data points to an obvious mid-Holocene increase in moisture availability in the eastern drylands of China, the more central Badain Jaran and Tengger Deserts, and the western Gurbantunggut Desert. However, the intensity of the increase in the central and western regions is still unknown. It has been shown that during much of the early and middle Holocene the Sahara Desert was much greener than today due to an increase in moisture

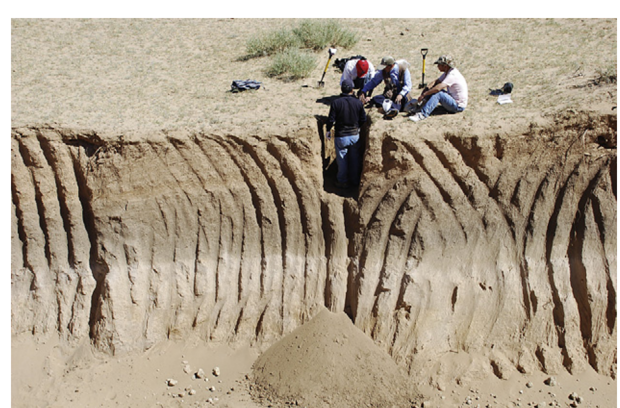

Fig. 12. Palaeo-soils (dark coloured in the middle of the sequence) of the middle Holocene in the dune areas of the Hunshandake (for scale see the people talking samples).

from an enhanced North African monsoon (Roberts, 1998; Yu and Harrison, 1996; Prentice et al., 2000; Bubenzer and Riemer, 2007). Future archaeological and palaeoenvironmental studies in China should attempt to quantify moisture levels in the deserts and sandy lands during the Holocene period and determine whether Chinese deserts, like their Saharan counterparts, experienced a similar greening during the early Holocene (Prentice et al., 2000).

6. Human activities and impacts in the drylands

The presence of numerous archaeological sites in China's deserts indicates a significant level of human activity in arid and semi-arid regions since the Neolithic Era. However, most of these sites have not been investigated and radiometrically controlled dating is absent for most. On the northeastern Tibetan Plateau and at the southern margins of the Badain Jaran Desert many sites of the early agricultural "Dadiwan culture" have been found and limited ages suggest that they date from ca. 7200 to 5000 yr B P (Institute of Archaeology, 1983). Archaeological evidence from the present climatically determined transition zone between animal grazing and farming suggests that the early agricultural Hongshan Culture, with sites densely distributed in eastern Inner Mongolia, developed as early as 6500–5000 yr B P (Mo et al., 2002).

It is still not clear whether these early human activities had a long-lasting impact on environmental conditions on a regional scale via changes in land use. We believe that the degradation caused by human activities in drylands cannot be easily rehabilitated by nature itself and that this change possibly has significant feedbacks to and impacts on the climate system. For instance, on the eastern Tibetan Plateau, palynological studies have shown that a nomadic influence on vegetation occurred by changing grass species as early as 7200 cal yr B P (Schlütz and Lehmkuhl, 2009) and that nomads at that time used fire to prepare large pastures (Miehe et al., 2009), resulting in significant changes in species composition and distribution. Interestingly, lacustrine records from the northeastern portion of the Tibetan Plateau suggest that no obvious human impacts occurred during the Holocene (Wischnewski et al., 2011).

Both during historical times and at present, important economic and social support systems have been quite common in the drylands of China. Agricultural cultivation was already widely practised on the margins of the Taklamakan Desert during the Han Dynasty (206 BC – 220 AD). Several ruined settlements with urban-type city walls have been found in the interiors of this sand sea, and timber remnants from one of the cities were dated to ~2000 cal yr B P. Historical descriptions from early times also confirm that there were large religious monasteries in hyper-arid desert areas, particularly during the Tang Dynasties (619–907 AD), a period characterized by a large expansion of Chinese Culture to the western regions (Yang, 2010). Rock sculptures from this period found in Pakistan's northwest deserts confirm a high-level of human activity in this part of the drylands during the last 2000 years, with significant evidence of continuous agricultural utilization (preservation of the former irrigation channels, our unpublished field data, 1997).

In a global context, drylands are regions where the earliest human activities have been documented (e.g., Hole, 2009). For instance, the earliest metal used by humans was copper and its earliest use was in association with farming in Iran and Turkey between 7250 and 6750 BC (Moorey, 1994). Recent studies have shown that the initial bronze production site in China was probably in the valley of the Heihe River (Black River), west of the Badain Jaran, as early as 2135 BC. One of the sources of these copper ores was located nearby, and was still mined in modern times. This area was a possible key region for the initial spread of bronze technology into eastern regions of China (Dodson et al., 2009). Large pieces of charcoal at the excavation site suggest further that substantial areas of woodland vegetation occurred around the sites (Dodson et al., 2009). Exhaustion of the wood supply resulted in the abandonment of this archaeological site for bronze manufacture. Archaeological evidence also indicates that people around the sites practised cropping of wheat and millet, and wheat seeds have been dated to 3800 yr B P (Dodson et al., 2009). At present this region is primarily covered by sand dunes although grasses and shrubs may be occasionally present. Comparing the present landscape with that found during the earliest bronze production, leads us to believe that the area could be one of the earliest cases of human-induced desertification, since the disappearance of the woody plants was directly caused by deforestation for metal manufacture.

In modern times, China's drylands are even more important environmentally and economically. The development of agriculture and industry in drylands has altered rivers, soils, and ecosystems to such a degree that major ecological rehabilitation and restoration measures have been ongoing since 1950. Abundant mineral resources have made the drylands a crucial component in the industrialization of China. For example, the diversion of water from the Heihe River, with headwaters on the northeastern Tibetan Plateau, has been the source of major debate among scientists in recent decades. The main course of the river is ca. 850 km long, flowing from the mountains in the northeastern Tibetan Plateau and emptying into a lake northwest of the Badain Jaran Desert. Since 2000, in order to ensure the safety of the 15,000 people living in the lower reaches of the river and to restore the ecosystem, 50% of the water has been diverted to the lower reaches each year (Yang et al., 2006).

China's nuclear agency is searching for places to store nuclear wastes and one of the criteria is that the region will in the coming 10,000 to 50,000 years remain as dry as today. The area northwest of Badain Jaran Desert was selected recently as a primary candidate for storage. However, if our understanding of palaeoclimates and our documentation of major Pleistocene environmental changes is correct, it is by no means clear that the climate of the region will remain as dry as at present. In all likelihood, dramatic and abrupt climate change will occur and this reality cannot be neglected for construction of such disposal and storage sites.

The semi-arid regions of China have also suffered greatly from land degradation, although the severity of the degradation is still debated (e.g., Mensching, 1990; Yang and Conacher, 2009). Safriel (2007) noted that only five attempts to assess land degradation at a global scale have been made by researchers or organizations since 1977, and none of the five assessments is a reliable source of information. A similar situation occurs with assessments of desertification in China. Administrative data suggest that about 2.64 million km^2, or 27.5% of China's total land area, has been affected by desertification (State Forestry Administration, 2005). However, another official report states that the total area of desertification is only 861.6×10^3 km^2, or only 6.9% of China's land area (Study Group, 1998). Disparities between these estimates of desertification demonstrate the need for further field-based examination of landscape change in the drylands in modern times.

Research has shown that total wetland area, as well as the total area impacted by desertification, correlate well with fluctuations in annual precipitation and temperature (Yang et al., 2007). However, we note that the severity of desertification, even on a local scale, is difficult to understand and quantify. For example, several researchers have examined the processes of desertification in the Hunshandake Sandy Lands and their conclusions are quite different or even contradictory. Using both Landsat TM and ETM + data, Liu et al. (2008) concluded that the area of active dunes increased by

2622 km^2 from 1987 to 2000 in the Hunshandake, while Wang et al. (2007), using a similar approach, concluded that the increase was just 1136 km^2 during the same period and in the same region.

Zhong (1999) compared aerial photography from the 1950s and Landsat TM imagery from the 1990s, and came to the conclusion that the active and semi-active dunes in all of China's sandy lands are undergoing a process of stabilization, and consequently concluded that desertification was not occurring. However, it appears that the selection of indicators used to quantify desertification has a significant effect on the assessment. An increasing NDVI (Normalized Difference Vegetation Index) trend from the 1980s has been interpreted as evidence of a decline in desertification in north China (Piao et al., 2005). This is consistent with an increasing trend in primary production between 1982 and 1999 in Inner Mongolia, documented from satellite derived light-use efficiency models (Brogaard et al., 2005). However, most geoscientists pay greater attention to the land surface change, and in particular to the areas occupied by shifting sands, when assessing desertification. We believe that the magnitude of change in NDVI is probably not sufficient to produce dune stabilization when these geomorphic indicators are taken into account. This points to the need to reconcile the results of different approaches in order to produce a clear picture of desertification in China.

Mason et al. (2008) believe that because of lags between the reduction of wind velocity and vegetation recovery that there is no obvious ongoing rehabilitation of the desertified areas in the Hunshandake. Although earlier studies have shown that wind intensity is a crucial factor in aeolian processes (e.g., Fryberger and Dean, 1979), it may not be the controlling factor in the desertification in Hunshandake because the area is generally characterized by intensive winds (high mean wind velocity and frequency of occurrence of the strong winds, Yang et al., 2011). It is obvious that a combination of biological and geomorphological indicators is needed for a comprehensive understanding of the desertification process. At present such indictors have not been applied consistently in China.

7. Conclusions

Abundant geomorphologic, lacustrine, pedologic, geochemical, and faunal and floral fossil evidence suggests that significant climatic fluctuations took place in the arid regions of China during the Late Quaternary. From evidence preserved in these drylands, we conclude that both semi-arid and arid deserts are very sensitive systems, and that features associated with climate-induced changes are not as long-lived as previously assumed. The occurrence of lacustrine sediments over an extensive portion of the dryland region suggests that it does not take a long time to form the sand seas, assuming that aridity increases along with the availability of a sufficient supply of sediment. Basins can be inundated rapidly with only moderate increases in moisture, as occurred at ~30 ka in the Taklamakan Sand Sea and in the Chaidamu Basin. In general, there is strong evidence of lake formation associated with significant increases in the precipitation/evaporation ratio in the western and middle portion of the desert belt during the late portion of MIS 3.

Remains of lacustrine sediments in the Taklamakan, Badain Jaran and Hunshandake are indicative of large lakes or swamps in these regions during the late Quaternary and even into the Holocene, although high-resolution chronologies are still lacking. Generally speaking, the entire desert belt of northern China experienced a relatively wetter period from 8 ka to 4 ka, although the length and intensity of wet conditions may have varied from region to region. Future studies should clarify whether this increase in moisture availability was sufficient to enable greening of the desert landscape, as occurred in the Sahara, during the early and middle Holocene.

Newly estimated values of evaporation from water bodies in drylands, at just one third of earlier published values, indicate that the lakes in mid-latitudes drylands can be sustained at much lower precipitation than previously assumed. Groundwater regimes in some lake systems like those in the Badain Jaran Desert of western Inner Mongolia are not well understood yet, and research focussing on the regional hydrogeology, geology, and geomorphologic processes is still needed in most of China's dryland regions.

Recent research on dust generation and transport, and on parameters controlling dune activity, raises questions about earlier approaches used to decipher palaeoclimatic conditions in the deserts of northern China. Future research needs to consider that the climatic signals captured in the loess deposits of Asia are quite complicated and that a much more systematic approach is needed to fully understand this climate proxy. In this context, studies have shown that loess from large alluvial fans, rather than from sand seas, are vital to infer palaeoenvironmental conditions in 'source' regions. Work arguing for a lacustrine origin for some of the oldest aeolian sediments underpins some of the problems, challenges, and difficulties relating to the precise interpretation of pre-Quaternary sediments in drylands. Recent results concerning the source of many loess sequences in China lead to the conclusion that loess accumulation does not necessarily require the occurrence of sand seas in the source regions. In this sense, a full understanding of the environmental changes in the drylands will be needed, with a focus on examination of the geological records on site, because there is a large difference between conditions sufficient for generating dust and conditions of a real desert landscape.

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Appendix. Supplementary material

Supplementary data related to this article can be found online at doi:10.1016/j.quascirev.2011.08.009.

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