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Understanding the Interactions between Climate Change, Landscape Evolution, Surface Processes and Tectonics in the Earth System: What Can the Studies of Chinese Deserts Contribute?

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Abstract: Due to large deserts on Earth surface a thorough understanding of climate change, landscape evolution and geomorphological processes having occurred in deserts is crucial for Earth System Science. The landscapes in deserts are, however, diverse and different over the globe with regard to their geomorphological nature, human activities and geological histories. In the last decades a great number of efforts have been put to the investigation of the initial timing of the occurrence of arid climate, e. g. in northwestern China. Silty sediments in the downwind directions have been used to deduce the histories of deserts. In general, there is a lack of knowledge about processes and landscapes in Chinese drylands between the initial Miocene silt sedimentation at desert margins and the late Quaternary multiple occurrences of wetter climate with assumed large lakes in many of the deserts in northern China. The geomorphological concept of three primary triggering factors, i.e., the sediment supply, sediment availability and transport capacity of wind, and additionally the underground geology need to be fully considered for a better understanding of the environmental histories of sand seas which should not be viewed as equivalent for deserts because sand seas cover between < 1% and ca. 45% of the desert areas in various continents dependent on a complex interaction between various processes of both exogenous and endogenous origins.

Key words: desert, sand sea, earth surface process, global change, Quaternary geology, geomorphology

1 Introduction

In the past 20 years the studies of deserts have become an exciting field of investigation in the global arena of science partly due to the important role of deserts for developing Earth System Science, and partly due to environmental pressure arising from rapid economic development and increasing population in drylands. On the other side, however, probably no other landscape is so contradictorily described and sensed as the desert. It is often associated with oil industry, oases, bare lands, useless, dangerous, relentless in literature, although residents in deserts see it as living space and luckiness for millenniums (Blümel, 2013). Desert, as a type of the main landscapes of Earth, occurs from hyper-arid to sub-humid climates. In terms of distribution, arid (including hyper-arid), semi-arid and dry sub-humid regions occupy about half of the land area on earth (Köppen, 1931; Goudie, 2002; Williams, 2014; Fig. 1). According to the Millennium Ecosystem Assessment (2005), 20.2% of the world population live in arid and semi-arid regions. Besides, 15.5 % of world population live in the sub-humid zones. Thus about one third of the world population occupies drylands, meaning that the studies of drylands are extremely important for the sustainable development of our planet in general and for drylands in particular.

From a geological point of view, all deserts on Earth have been formed by a variety of processes, and history of deserts may vary greatly from region to region. Although the report of climate change in arid regions of western China (Richthofen, 1877) was one of the earliest discoveries of Quaternary climatic instability, deserts today belong to the least understood part of the Earth. In the classic literature, deserts were described as the outcomes of aridity (e.g., Zhu et al., 1980), and

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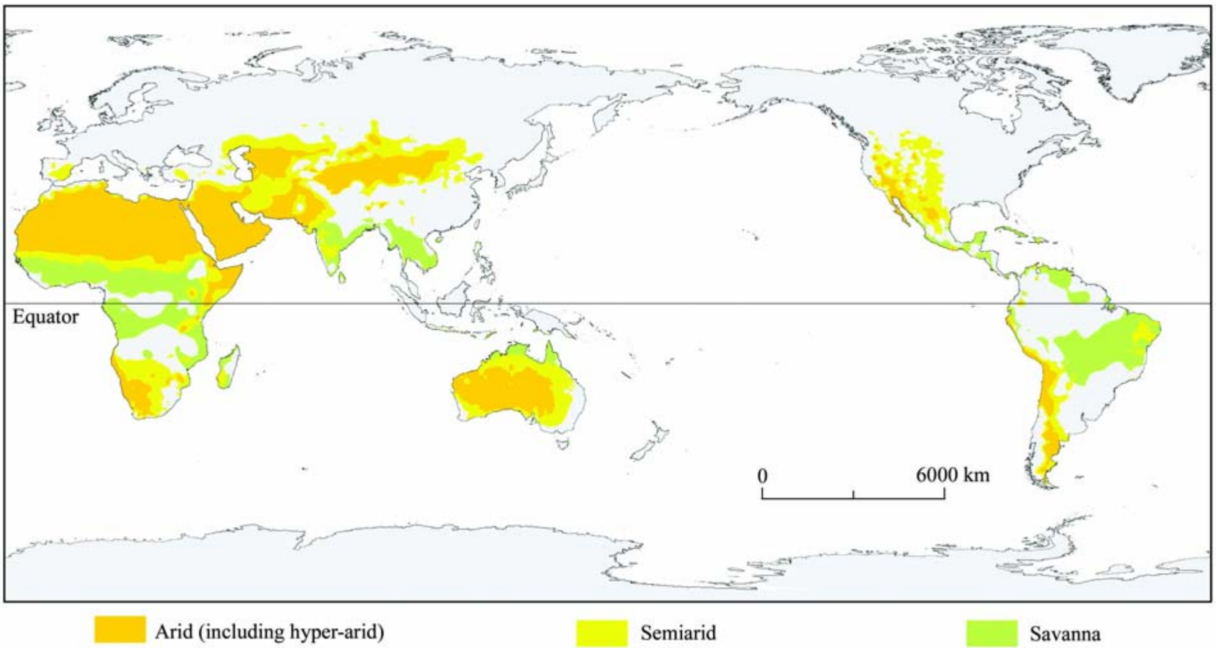

Fig. 1. Global distribution of drylands and savannas.

aerodynamic processes are the predominant process forming the landscape in the hyper-arid regions (e.g., Hövermann, 1985). The recognition of changing processes and the interaction between different processes has been a significant step in interpreting geological evidence of landscape and palaeoclimatic changes in deserts (e.g., Kocurek and Lancaster, 1999; Eitel et al., 2002; Lehmkuhl et al., 2012; Williams, 2015). It is found out that there has been a long history of fluvial and aeolian interactions in African deserts, e.g., the Sahara and in the arid regions of Australia, the large drylands in the subtropics (Williams, 2015). Sedimentological sequences in the Sahara and Australia indicate that the dunes there were fed by alluvial deposits, and vice versa the fine-grained valley-fills are often reworked aeolian sediments (Williams, 2015). River silts and desert loess can provide important paleoenvironmental information as shown for the Namib Desert, southern Africa (Eitel et al. 2005) and the Peruvian coastal deserts (Eitel et al. 2005a). The alteration of fluvial and aeolian deposits is often triggered by climatic fluctuations in many parts of the deserts (Williams, 2014). During the Pleistocene glacial epochs, dunes in the western Sahara expanded onto the continental shelf, accompanied by southwards shifting desert dunes and a large-scale contraction of Guinean forest in West Africa (Goudie, 2002). Also in the Arabian Peninsula, the desert landforms and their long-term changes has been strongly shaped by the interaction between wind and water. Various sedimentary profiles show that fluvial and alluvial processes were active in the early to mid-Quaternary, although runoff under present climates is rare and largely confined to the mountains (Pain and Abdelfattah, 2015).

The extensive drylands in China occupy more than one third of Chinese territory (Zhu et al., 1980). The history of Chinese deserts should be related to the tectonic uplift of the Tibetan Plateau, the largest and highest plateau on Earth (Manabe and Terpstra, 1974; Zhu et al., 1980; Derbyshire and Goudie, 1997; Zheng et al., 2015). The vertical variation of the topography does have an impact on the diversity of aeolian reliefs in China (Jäkel, 2002). The powerful tectonic geomorphodynamics are expressed in very high erosion potentials and high rates of sediment production (e.g., Derbyshire and Goudie, 1997; Liu et al., 2015) which are advantageous for the formation of sand seas (Yang et al., 2012; Fig. 2). Due to the position of the northern margin of Asian summer monsoons and the north-hemispheric westerlies that influence the hydrology of Chinese deserts, the palaeoenvironmental records in the deserts of China are crucial keys for understanding the history of Asian monsoon systems and for interpreting the variations of the westerlies in Asia. Furthermore, the deserts of China are a major source area for global atmospheric dust (Prospero et al., 2002) and play a significant role in the global bio-geochemical cycles and climate system dynamics (Jickells et al., 2005; Uno et al., 2009). In this paper we aim to briefly review the current understanding about the initial occurrence of the desert landscapes in China and related Quaternary palaeoclimatic and landscape changes. Our analysis on the geological evidence from deserts could be helpful for understanding the interactions between climate change, landscape evolution, surface processes and tectonics in the Earth

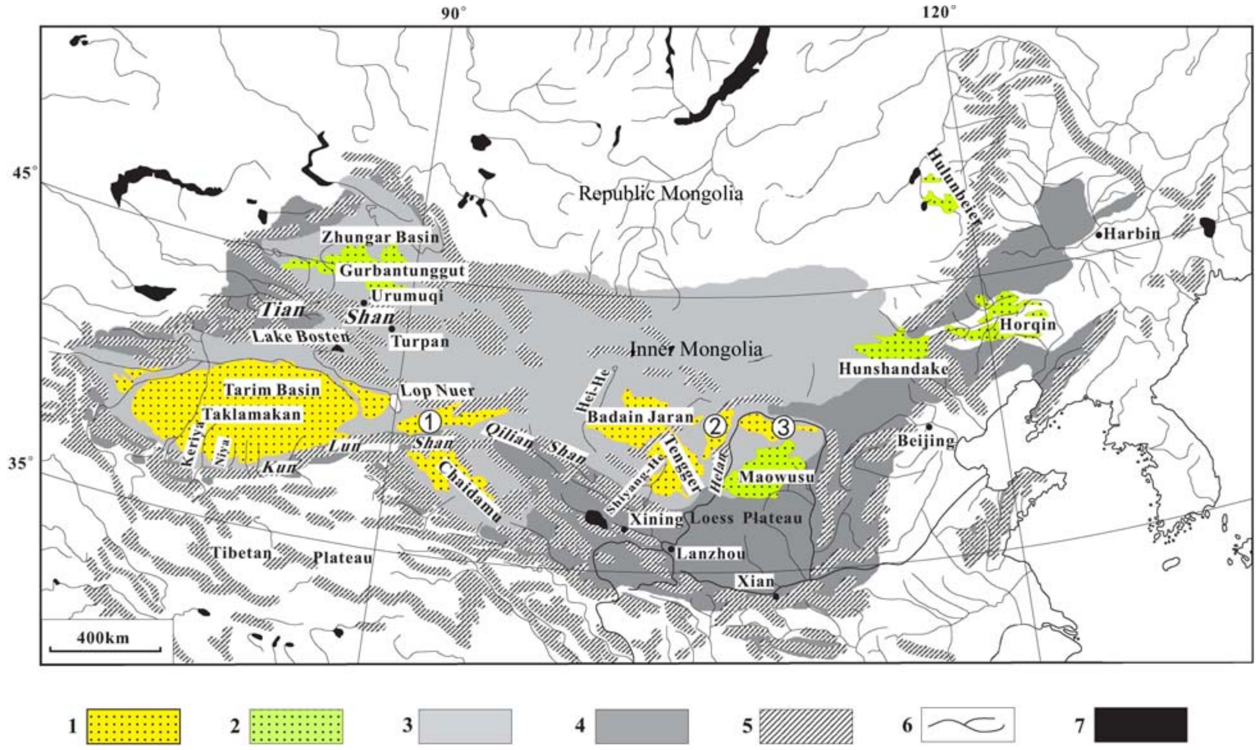

Fig. 2. Distribution of the desert landscapes in China, showing that large sand seas occur in the endorheic basins or in the lower reaches of rivers and streams with headwaters in the surrounding mountains.

1: sandy desert (sand sea), 2: sandy land (stable dune field), 3: gravel desert (Gobi), 4: loess, 5: mountain range, 6: river, 7: lake. Small sand seas are indicated as ①: Kumtag, ②: Wulanbuhe and ③: Kubuqi.

System and particularly in the drylands, and for identifying knowledge gaps for future studies.

2 Initial Formation of Deserts as Outcome of Tectonic and Climatic Impacts

In the geoscience community, the primary causes for the emergence of drylands in China are unambiguously understood, i.e. locality far away from oceans and additionally enhanced by the blockage of moisture pathways by mountains and plateaus (e.g., Köppen, 1931; Zhu et al., 1980). The timing of initial occurrence of desert landscapes in China is, however, distinctly differently interpreted from various geological evidences. The Taklamakan Desert, as the largest sand sea in China (Table 1), is of particular importance for understanding the environmental changes and landscape evolution in western China, and for deciphering knowledge about the tectonic uplift of the Tibetan Plateau. Zhu and his colleagues mapped the distribution of aeolian dunes in the Taklamakan in the 1950s and published their results in 1981 (Zhu et al., 1981). They concluded that the Sand Sea of Taklamakan has been gradually formed since the middle Pleistocene on the basis of the occurrence of alluvial and fluvial gravels and coarse sands underlying the aeolian sands in its southwestern parts. And their chronology was deduced from the nature of the loose fluvial sand and silt, and their stratigraphy was obtained from core descriptions while water wells were drilled to 300 m depth. Zhu et al. (1981) demonstrated that the geomorphic processes of forming the alluvial fans and fluvial deltas were active during the early Quaternary in the areas of Taklamakan, and the sand sea came into appearance afterwards (Zhu et al., 1981).

Table 1 Area of sand seas (sandy deserts) and fields of stabilized dunes (sandy lands) in northern China (from Zhu et al., 1980; Chen, 1994; Yang et al., 2012, for locations see Fig. 2).

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

Note: — no data.

In more recent decade, new insight into the initial occurrence of the Taklamakan has been successfully obtained from the chronology of aeolian deposits found in the mountains south of the desert. It is generally assumed that aeolian silts and sands of the mountains in the south must be blown by wind from the Taklamakan. This assumption is in agreement with the predominant wind directions in the Taklamakan (Zhu et al., 1981). From the occurrence of wind-blown silt and its magnetostratigraphic chronology of a thick Cenozoic sequence in the southwestern margin of the Taklamakan, Sun and Liu (2006) suggested that the hyper-arid climate has prevailed in the Tarim Basin since 5.3 Ma ago. Other studies using similar approaches yielded quite different results from other sections in the region. Sun et al. (2011) applied palaeomagnetic and ESR dating to two parallel terrestrial sediment sections in the Mazatagh Mountains in the central Taklamakan, and dated the timing of the initial desert formation to ~ 3.4 Ma. From the changes in color index and magnetic susceptibility of the strata, they interpreted that an intensification of aridisation occurred at ~ 2.6 Ma, coincident with the onset of the Northern Hemisphere glaciations (Sun et al., 2011).

The aeolian sediments found in the marginal mountains and in the Mazatagh Mountains could be of late Oligocene to early Miocene age according to a more recent study by Zheng et al. (2015). Zheng et al. (2015) demonstrated that the Taklamakan was formed between ~26.7 Ma and 22.6 Ma ago according to their U–Pb datings of the zircons in the volcanic ash underlying the aeolian sediments in the region. This age is coincident with the tectonic uplift of the Tibetan-Pamir Plateau and the Tian Shan (Zheng et al., 2015).

The second and third largest sand seas in China are the Badain Jaran and Tengger Deserts, respectively. These two large deserts are located in the western Alashan Plateau and there is no high mountain nearby in their downwind directions. Thus it is difficult to deduce the initiation of the deserts from potential aeolian silt deposits sourced from the deserts, as having been done for the Taklamakan. Thus on-site deep drilling has been applied to investigate the history of the deserts. A 276 m deep core was drilled in the central Tengger Desert in alluvial-fluvial and lacustrine-fluvial deposits with inclusion of dusts in the lower part, and aeolian sand on the upper part (Li et al., 2014). Palaeomagnetic chronology and ESR dating indicate that continuous aeolian sand components appeared first at 0.9 Ma ago, and this turn was suggested to mark the initial formation of the Tengger Desert. In the same core the sand content became the dominant fraction after 0.68 Ma and this was considered as evidence for the spatial expansion of the Tengger Desert (Li et al., 2014).

Earlier the Pliocene was also suggested as the initial timing of the dune landscape in the eastern portion of the desert belt in northern China on the basis of stratigraphical correlations (Li and Dong, 1998). The extensive distribution of lacustrine sediments underlying the aeolian sands and their OSL chronology, however, suggest that many of the current aeolian dunes in the Hunshandake Sandy Land were first formed after desiccation of the lakes ca. 4000 years ago (Yang et al., 2015), and others probably during the late Pleistocene, but not earlier (Yang et al., 2013).

3 Landscape, Surface Process and Climatic Changes during the Late Quaternary in the Deserts of China

Different from the hypotheses of continuous decreasing trends of humidity during the Quaternary in Central Asia (e.g., Berg, 1907), studies in the desert areas have shown that repeated epochs of wetter climate, accompanied by distinct changes in the landscape and surface processes, have occurred in the deserts and along the deserts margins in China and in the neighboring countries (e.g. Gibert et al., 1995; Grunert et al., 2000; Grunert and Dasch, 2004; Hülle et al., 2010; Yang et al., 2011; Lehmkuhl et al., 2012; Williams, 2014). Thick outcrops of lacustrine sediments both overlying and underlying aeolian sands are widely present in the Badain Jaran, Tengger and Taklamakan deserts (Fig. 3), meaning that lakes occupied the desert areas for a relatively long period of time, although detailed chronological studies about such palaeoclimatically promising sections are extremely rare due to remoteness and uncertainties in dating. A few of the OSL (Optically Stimulated Luminescence) ages from underlying and overlying aeolian sands at a section in the Taklamakan provide a framework for the timing of a palaeolake. In the center of the Taklamakan, between 1100 and 1150 m a.s.l., the occurrences of lakes were dated to ca. 2700 yrs, ca. 30,000 yrs and the time between 30,000 and 40,000 yrs, respectively (Yang et al., 2006; Fig. 4). Provided that today's topography is roughly similar to that of 40,000 yrs ago, the lacustrine outcrops would indicate the occurrence of a rather large lake occupying more than half of today's Taklamakan, as shown in the digital elevation models created using SRTM data (Yang et al., 2011). Holocene wetter climates in the Taklamakan have been identified directly from the lacustrine sediments (Yang et al., 2006), fluvial sediments along rivers (Yang et al., 2002) within the desert and historical descriptions about well-developed desert rivers and lakes (Jäkel, 1991; Lehmkuhl and Haselein, 2000; Yang et al., 2006a). The sediments in the forelands of the Kulun Mountains along the Keriya River were recognized as typical glacial-fluvial deposits by Hövermann J. and Hövermann E. (1991),

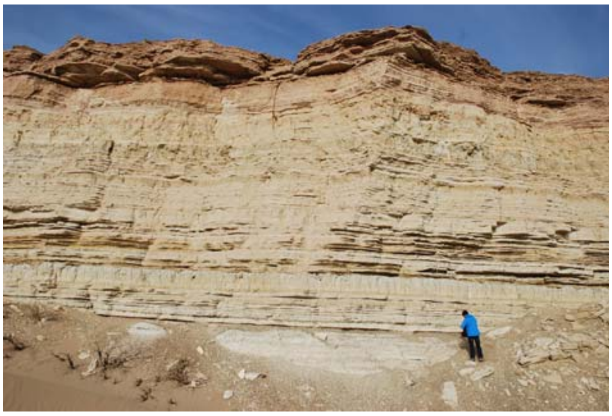

Fig. 3. Remnants of laminated lacustrine sediments at the northwestern margin of the Badain Jaran Desert.

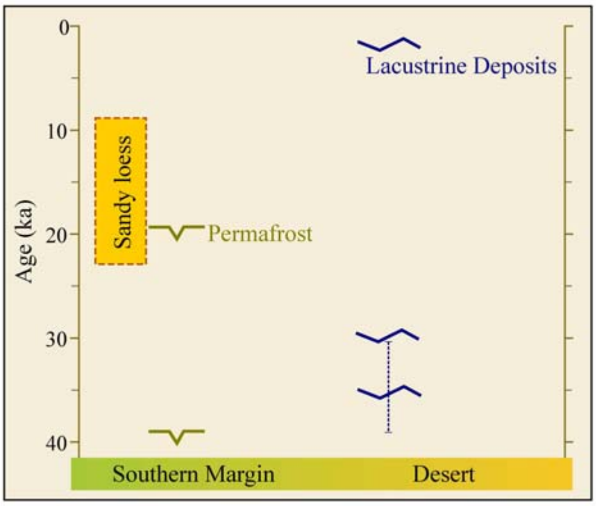

Fig. 4. Humid climate interpreted from lacustrine sediments in the Taklamakan Desert and times of temperature decrease by ca. 14°C, deduced from permafrost relics at its southern margin (modified from Yang et al., 2006).

suggesting that the southern margins of the Taklamakan were shaped by glacial-fluvial processes during the deglaciation periods (Yang et al., 2002).

In contrast to the interior of the Taklamakan, lacustrine and aeolian sediments at its margins have been intensively studied to reconstruct palaeoclimatic changes in the drylands of Asian middle latitudes. Changes in the stable carbon isotope concentration of organic matter in a core from Lop Nuer, the former large lake in the eastern Tarim Basin indicate that there was relatively abundant moisture in the region between 20 and 14 ka (Luo et al., 2008). Geochemical data and ostracod assemblages from a Bosten Lake core (located at the northeastern margin of the Taklamakan) suggest rapid and repeated shifting between dry and wet intervals during the Holocene (Wünnemann et al., 2003, 2006; Huang et al., 2009). Reinterpretation of data from the Bosten Lake in Wünnemann et al. (2003, 2006) shows a long lasting wetter period from ca. 8 to ca. 1 cal ka BP (Chen et al., 2008). While the moisture sources in the Taklamakan often are associated with westerlies, Mischke and Wünnemann (2006) interpreted the expansion of the Lake Bosten as an impact by the Indian monsoon.

Palynological data and radiocarbon chronology of a lacustrine section in the Yili Valley located northwest of the Taklamakan Desert indicate distinct changes in effective moisture during the past 15 ka too. The pollen records show that rather humid climates occurred during the Bølling-Allerød (15–12.9 cal ka BP), in the early Holocene (10.6–7.6 cal ka BP) and the late middle Holocene (6.5–5.2 cal ka BP) while drier climates appeared in the early Younger Dryas (YD) (12.9–12.0 cal ka BP) and in the early mid-Holocene (7.6–6.5 cal ka BP), and in the late middle Holocene between 5.2 and 3.3 cal ka BP (Li et al., 2011). A new study about the loess-palaeosol sequences from the northern slope of the Tianshan Mountains and the Yili valley, however, suggests that the Holocene palaeosol, arising from the moister conditions generally, formed after ~6 ka, and the accumulation of unweathered loess relating to a dry climate prevailed during the early Holocene (Chen et al., 2016). Although these records are located in desert margin areas, it is to assume that the climate within the desert should have fluctuated considerably also while distinct climatic variations occur in the close vicinities. This is in accordance with the perspective that desert margins are not linear borders but form separate areas of focus defined by climate-induced shifting margins and characterized by their own geoecodynamics (Eitel et al., 2007, 2007a).

Referring to the magnitude of palaeoenvironmental changes, much more dramatic landscape and surface process changes should have occurred in the Tengger and Badain Jaran Deserts during the late Quaternary. The Tengger Desert was characterized by large wetland areas during the late Pleistocene. High lake terraces enable an interpretation of warm-humid climates, supported by chemical palaeoclimatic proxies and fossil pollen assemblages (Zhang et al., 2002). The shells collected from the high lacustrine terraces around the former terminal lake of the Shiyang River (in the center of this desert) were radiocarbon dated to between 35 and 22 ka BP, and the area of this single lake was almost 16,000 km^2 in area (Pachur et al., 1995; Zhang et al., 2002), i.e., ca. one third of the entire desert. This mega lake desiccated at ca. 18 ^{14}C ka BP and reemerged again at ca. 13 ka BP (Pachur et al., 1995; Zhang et al., 2002).

The highest dunes on Earth with a maximal height of 460 m occur in the Badain Jaran Desert, accompanied by permanent lakes in the inter-dune depressions. Although many of the lakes contain salty water or even brines (Yang and Williams, 2003), the remnants of freshwater snails in lacustrine deposits indicate that the present salt lakes were filled with fresh water at ca. 10 ka ago. The available data suggest that the total lake area was probably nine times as large as at present in the Badain Jaran during the middle Holocene, suggesting a wetter climate at that time (Yang et al., 2010). Using multivariate analyses and generalized additive modeling of species response curves from a dataset of 26 lakes containing diatoms in the Badain Jaran Desert, Rioual et al. (2013) established a transfer function showing the close relationship between the electrical conductivity (EC) of lake water and the diatom assemblages. For the recent 50 years this transfer function was successfully applied to reconstruct EC changes. The relationship between EC and climate was found to be weak on the short time scale since the water surfaces and depths of these lakes did not change distinctly during the last two decades probably due to mediation potentially by the hydrogeological settings (Rioual et al., 2013).

The magnitude of the palaeoclimatic and landscape changes has been much greater in the eastern portion of the desert belt than in the western in northern China. For instance, the Hunshandake (Otindag) Sandy Land, a sandy area covered primarily by stabilized dunes and located in the semi-arid zone of eastern Inner Mongolia (Fig. 2), was characterized with soil formation under much wetter climate between 9.6 ka and 3 ka (Yang et al., 2013). Although the precise duration of the wetter period might change from site to site, the aeolian processes were dormant to a large degree in the eastern portion during the middle Holocene as the occurrence of palaeosols and their OSL chronologies indicate (Li et al., 2002; Lu et al., 2005; Mason et al., 2009; Li and Yang, 2015).

4 Discussions

As the aforementioned research results demonstrated, the establishment of the desert landscape in northern China has been ultimately triggered by the enhanced climatic aridisation probably arising from the tectonic uplift of the mountains and plateaus surrounding these deserts, and potentially also related to the onset of the Northern Hemisphere glaciations, although the continental nature is primarily due to the long distance to oceans. The climatic change occurs in deserts in China and elsewhere as the Earth System evolves. The aridity of Australia is, for example, due to the continental shift from a near-polar climatic zone into a zone of tropical and subtropical climates in the past 50 million years (Gale, 1992), but the geological and botanical evidence suggests that the present interglacial period is drier than the previous interglacial (Martin, 2006). A detailed reconstruction of desert landscape changes in China would reveal the palaeoclimatic fluctuations in the mid-latitudes of Asia, and the interaction between various processes of both exogenous and endogenous origins. The available research outcomes have provided a very valuable framework and gives orientation for investigating the formation and changes of deserts in China, although many controversies co-exist. To overcome the difficulties in interpreting the representatives of site-based geological records, the potentials of large regional scale databases for assessing palaeoenvironmental change should be explored (Scuderi et al., 2015).

In Chinese terminology, deserts actually refer to landscapes of sand dunes and sand sheet only (Zhu et al., 1980). In this sense the establishment of arid climate cannot be an equivalent for the formation of sand seas. It is, however, impossible to judge the extension and coverage of sand dunes in the source areas from downwind sedimentary sequences. Studies about provenances of the aeolian sands in the Hunshandake Sandy Land (Liu and Yang, 2013) and in the Taklamakan (Yang et al., 2007) have shown that the dune sands within a desert may be different from catchment to catchment as the aeolian sands in these two sandy environments are mainly reworked fluvial and alluvial sediments constrained to the individual local catchments. Using mineral and sedimentological compositional data of various sediments and wind data, Lancaster et al. (2015) showed that dune sands in the Owens Lake basin, California, southwestern USA originate primarily from the Sierra Nevada via the Owens River from the north as well as from granitic rocks in the Coso Range to the south. For the further study of Chinese deserts systematic analysis showing sediment cycles, relief dynamics and transport pathways and detailed chronology of major events is needed. But it would be much more difficult to do this kind of research in the deserts like Taklamakan due to a much larger extension and longer history of the aridity.

In a global comparison, the availability of aeolian sediments is much more abundant in Chinese deserts since active and stable dunes occupy as much as ca. 45% of drylands in China (Zhu et al., 1980; Fig. 2). Active sand seas cover between 15% and 30% of the arid areas in the Sahara, Arabian Peninsula, Australia, and Southern Africa (Goudie, 2002), and only less than 1% of the arid zone in the Americas (Lancaster, 1995). These numbers reconfirm that sand seas should not be considered as equivalence for drylands. In the palaeoenvironmental change studies one needs to keep in mind that drylands are diverse in their climate and topography not only today but also in the past (Blümel, 2013). Reconstructions of past environments should consider the spatial variability in these environments (Thomas et al., 2012), as well as their different sensitivity to climate changes (Lancaster et al., 2013; Telfer and Hesse, 2013).

The analysis of the loess and sandy silts supposedly derived from the sand seas suggested a much older age of the dune fields in western part of the Chinese desert belt, i.e., Pliocene or Miocene. The numerical dating of the sand sea sediments does not necessarily provide the initial occurrence of the sand seas but shows the direct association with the current landscape. In this sense, both approaches are crucial for the understanding of the landscape evolution. It is urgently needed to investigate the intermediate stages and development of the landscape between these two dates. The classic theory of the sedimentary interdependence between sand seas and loess has been challenged by the new studies demonstrating that the Yellow River should have provided sediments directly to the Chinese Loess Plateau and the sandy lands north of the Loess Plateau (Stevens et al., 2013). The bases of the aeolian dunes in the Kubuqi Desert were mainly dated to the Holocene (Yang et al., 2016), consistent with historical descriptions showing that many parts of this desert were inhabited during the Han (206 B.C.–A.D. 220) and the Tang (A.D. 608–907) dynasties (Wang, 1991; Yang et al., 2016). These younger ages, however, cannot offer insights about the local environments during the Miocene or earlier, but truly confirm that the current Kubuqi dune field is mainly formed during the Holocene.

In the scientific community investigating aeolian geomorphology, it is widely accepted that the formation of a dune field is controlled by three factors, i.e., (1) sediment supply, (2) sediment availability, and (3) the transport capacity of the wind (Kocurek and Lancaster, 1999). Studies in the Badain Jaran Desert have shown that the underground geology is another factor impacting the nature of the dunes (Yang et al., 2011a). Thus, aridity alone is not sufficient for the emergence of the dunes but mainly controls the sediment availability through vegetation coverage. In contrast, dunes are not limited to the drylands, either (Lorenz and Zimbelman, 2014). After detailed investigation of eight sedimentary sections and their OSL chronologies, Qiang et al. (2016) discovered that the distribution of aeolian sands was mainly dependent on the sediment supply in the dry Gonghe Basin of the north-eastern Tibetan Plateau and there has been no apparent relationship between past dune activity and downwind loess deposition in this region. Thus, aeolian activities might be an indicator of increased sediment supplies, but not necessarily proxies for aridity. Also in the Strezlecki and Tirari Deserts of Australia stronger dune activities took place periodically during the last 70,000 years, but not consistent with changes in climate either, according to OSL ages from 26 sites in these two deserts (Fitzsimmons et al., 2007). On a glacial-interglacial time scale it was much colder during glacials with greater aeolian activities but runoff normally associated with humidity may have been much higher also, at least seasonally in Australian drylands (Hesse et al., 2004).

While loess in the downwind areas is indicator of aridity in its desert source regions (e.g., Liu, 1985), sandy loess or desert loess found in present-day desert and desert margins indicates actually less arid environment. The Nazca-Palpa region in southern Peru, i.e., the northern portion of the Atacama Desert, is arid due to the impact of the cold Humboldt ocean currents. Eitel et al. (2005a) discovered desert loess at the desert margin area of the coastal desert and they interpreted the loess as evidence for a wetter climate in the early and middle Holocene. Their rationales for association of the desert loess with wetter environment are that a reasonably dense grass cover is needed to keep desert dust to be trapped and to form a stable loess mantle (Eitel et al., 2005a).

Although the level of human impact is generally lower in deserts than in many other landscapes on Earth, human activities do have a long history in deserts and have changed many parts of deserts from nature to cultural landscapes (e.g., Mensching, 1990; Seuffert, 2001; Mu et al., 2014). In the drylands of Syria, for example, rain-fed agriculture and transhumant herding prevailed over ten millennia and the problem of sustainability has developed only over the recent 70 years due to the dynamic interplay between various natural and social factors (Hole, 2009). Many of the land use histories can only be known after careful studies of detailed historical data, like the case in eastern Inner Mongolia of China. A district in the present-day semi-arid eastern Inner Mongolia was transformed from traditional animal grazing to lands for cultivating crops and then degraded in the 18th Century, coordinated by foreign missionaries who initially aimed to eliminate the hunger of peasants in that area at that time (Zhang et al., 2015). Human activities do have enabled vegetation and soil degradation in drylands to an unexpected degree, and may even cause farmland aridisation in drylands (e.g. Eitel et al., 2002).

5 Conclusions

The landscapes in deserts exhibit spatial heterogeneity and temporal diversity in terms of geological history in China and in other arid regions of the world. The studies of the environmental changes in deserts can reveal the mysteries of complex interactions between climate, landscape, surface processes and tectonic activities. The deserts in China are of particular significance for a better understanding of Earth system because of their geographical locations in a tectonically active environment and being jointly influenced by two large climate systems, i.e., Asian monsoon systems and Northern Hemisphere westerlies. The birth of arid climate in China and in the middle latitudes of Asia can be traced back to Pliocene and Miocene, consistent with the initial tectonic uplift of the Tibetan Plateau, as the aeolian silty sediments in the mountains south of the Taklamakan Desert indicate. Crucial questions like, how did the landscape in the Taklamakan and in other sand seas look like while this kind of silty sediments were deposited, or were these silts directly from which regions of dunes, remain widely unsolved. The occurrence of large lakes in the deserts during the Late Quaternary suggests that the current dune landscape was formed after the desiccation of these lakes and there have been multiple hydrological fluctuations in the late Quaternary in the deserts of northern China, and in other deserts of the world too. Much more than several patches of deserts in China and beyond were sites of ancient cities, confirming that some of the drylands are indeed man-made to a large degree. Revealing the palaeoenvironmental and landscape evolution histories between the initial birth of aridity in northern China and the establishment of the sand seas by clearly demonstrating the production, transport pathways, accumulation and remobilisation of aeolian deposits in the sand seas and the mechanisms triggering these processes both spatially and temporally would greatly contribute to the development of the Earth System Science.

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About the first author

Xiaoping YANG's research interests include deserts and their geological and historical changes, especially geomorphology and paleoclimatology during the Late Quaternary. He has intensively worked in the Taklamakan Desert, the Badain Jaran Desert, the Kubuqi Desert and in the Hunshandake Sandy Land to better understand the landscape and palaeoclimatic changes in drylands and the interactions between man and the environment. His research has been published in internationally reputable journals and he has received a number of very prestigious research awards, e.g., Huang Jiqing Award from Huang Jiqing Foundation in China (2008), Farouk El-Baz Award for Desert Research from the Geological Society of American (GSA, 2010) and the Humboldt Research Award from the Humboldt Stiftung/ Foundation, Germany (2016). He has been editing Quaternary Science Reviews and Quaternary Research for about a decade and has been a GSA Fellow since 2014.