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Geomorphological Evolution and Palaeoenvironmental Change in the Western Alashan Plateau, China

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ABSTRACT

Although neotectonic activity is considered to be the main factor of the terrain evolution of the Qinghai Tibet Plateau and its surrounding high-altitude areas, further geomorphological analysis and literature analysis are needed for the understanding of the geomorphic evolution and the Quaternary environment change of the western area of the Alxa Plateau near the northern Tibet Plateau. The purpose of this study is to investigate the distribution of site-specific geomorphic units of the landforms developed in the vast topography of Ejina Basin (Western Alxa), in order to identify the geostructural and climatic causes of the geomorphic landscape and its impact on the change of paleoenvironment. At present, the climate and hydrological conditions in Ejina are relatively monotonous and stable. In addition to tectonic dynamic factors, the most widely distributed landform in the basin is climate landform. There are both geomorphological and sedimentological anomalies of Aeolian landforms occurred in the whole basin, indicating that the underlying surface effect (retention effect) of river (Ejina River) and its related uneven ground and weak wind erosion (deflation) process in the nearby area may be the important factors controlling the formation of Ejina dunes, rather than the arid climate. It is believed that the extensive interaction between the aeolian and fluvial processes is the main mechanism of the regional geomorphic difference in Ejina Basin. According to the comparability of regional geomorphology and sedimentology, the period of the formation of relic geomorphology in the edge of Ejina Basin can be reasonably attributed to the local glacial maximum of the last glacial. The geomorphic transformation from quasi plain and desert valley to desert plain, the appearance of widely moving sand dunes and the presence of large ancient lake geomorphology all indicate that the drought index of Ejina Basin is increasing on the scale of geomorphic formation. Paleogeomorphological and chronological evidences show that the climatic and hydrological conditions of the basin in the last glacial period and the early Holocene are much better than those at present. For example, the average annual precipitation in the area before 39-23ka BP is between 60-350 mm (about 36 mm today), but there are large waves in the Holocene. The coexistence of various climates and landforms in Ejina Basin and the resulting geomorphic diversity should be the composite result of various geomorphic processes and surface processes besides glaciation. The low aridity (relative humidity) in the Ejina Region in the late Pleistocene may be the result of the enhancement of the westerly rain belt and the weakening of the Asian Winter Monsoon in the arid region of Central Asia.

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1. Introduction

It is of great significance to understand the climatic history of the desert landforms in the late Quaternary in China for understanding the airification/aridity of the interior of Central Asia and the evolution of the East Asian monsoon climate and the westerly climate systems [1-17]. At present, the distribution of arid areas in China can be expressed by annual precipitation. The extremely arid (< 100 mm) and arid areas (100-250 mm) are distributed in the central-northern and northwestern regions of China, while the semi-arid areas (250-500 mm) are mainly distributed in the east-northern regions (Figure 1). However, during the late Quaternary, China's sandy deserts and desert areas were affected by the infiltration of monsoon climate and the related significant increase of humidity, and many of them were in the transition between the eolian and the lacustrine environment [7,18-20], leading to great changes of the general arid environment in northern China. Large deserts such as Badanjin Desert and Taklimakan Desert and the lake water levels in these desert basins have made obvious response to the environmental changes from early to middle Holocene, especially the changes of intensity and precipitation/evaporation rate of the westerlies [7,19]. Therefore, China's deserts and desert margins are highly sensitive to climate change.

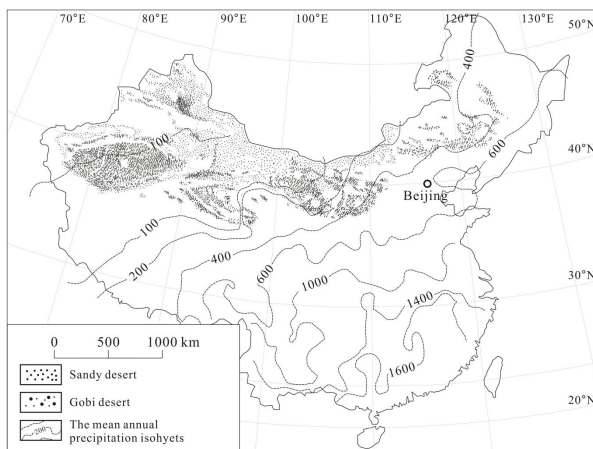


Figure 1. Distribution of the deserts and the annual mean precipitation in China

At present, China has only carried out extensive environmental monitoring on a small portions of desert areas, and the basic environmental information in most desert areas is often incomplete, or even can not be obtained at all [21]. At present, the available clues reflecting the environmental history of China's desert areas are largely derived from the evidences of loess and paleosol sedimentary sequences in desert margins or remote areas [3, 13-14, 22-23]. Limited by these data being not available, it is difficult

to assess the impact of current environmental change and understand how the desert system can cope with past climate change. A more comprehensive understanding of these desert environmental systems requires extensive use of new methods and approaches to characterize and monitor deserts in China [21].

There is an academic term in geomorphology, named "geomorphodiversity", which was proposed and defined by Panizza [24] and Testa et al. [25]. It is an important evaluation method for geomorphic characteristics and geomorphogenetic dynamics of a landform. This concept draws on similar and well-known terms of "biodiversity" and less well-known terms of "geodiversity" [26]. Based on these two disciplines, a new term in climate science, "climatediversity" has recently been proposed by the climate academia [27]. Due to the rapid development of the earth system science, the geological and climatological circles are now actively emphasizing on a new comprehensive science integrating "biodiversity", "geodiversity" and "climatediversity" [27], in which "geomorphodiversity" is regarded as an important component. It is defined as a discipline to identify the complexity and diversity of different geomorphic types of landform units under different environmental conditions and to explain the related geomorphogenetic mechanism. From this point of view, valuable information can be obtained from different geomorphogenetic landforms through reasoning and hypothesis, so as to better understand the geomorphic factors driving the formation of current geomorphology. From this point of view, valuable information can be obtained from different geomorphogenetic landforms through geomorphic classification, similarity reasoning and hypothesis, so as to better understand the potential factors driving the formation of current landforms.

On the Mongolian Plateau in Central Asia, there are more than 1.3 million square kilometers of Gobi (stone) deserts, which are composed of wide and shallow basins. The smooth rock particles on the ground surface of these deserts are filled with sand, silt/clay, pebble or more common gravel [28]. These Gobi desert landscapes, especially the Alashan Plateau and its surrounding deserts, are considered as the main sources of dust emission in Central Asia [29-31]. Ejina Basin, located in the west of Alashan Plateau, is the center part of the Gobi desert belt in the Mongolia Plateau, and also the closed end area of the Heihe River Basin, the second largest inland river basin in China (Figure 2). In terms of climatology, Ejina Basin is located in the northern margin of the low-altitude Asian Summer Monsoon and also in the latitude ranges of the high-altitude westerlies (Figure 3). Therefore, the basin has potential significance for understanding global climate change

and the response of plateau region to climate change. Tectotically speaking, the Alashan Plateau is an ancient stable block, but it has become active since Mesozoic ^[22]. The geomorphic and environmental evolution of the area is influenced by the tectonic stages caused by the compression of Eurasian, Indian and Pacific plates. Therefore, the study of geomorphology and paleoenvironment of the area also provides evidence for the study of the environmental impact of the uplift of the Qinghai-Tibet Plateau and the formation of the East Asian Monsoon ^[22, 32]. Up to now, however, there are few documents about the evolution of geomorphology and Paleoenvironment in the Ejina Basin. This paper is devoted to the geomorphic study of desert landscapes in the Alashan Plateau in northern China, in order to get a new understanding of the geomorphodiversity of Ejina Basin and its related late Quaternary climate change.

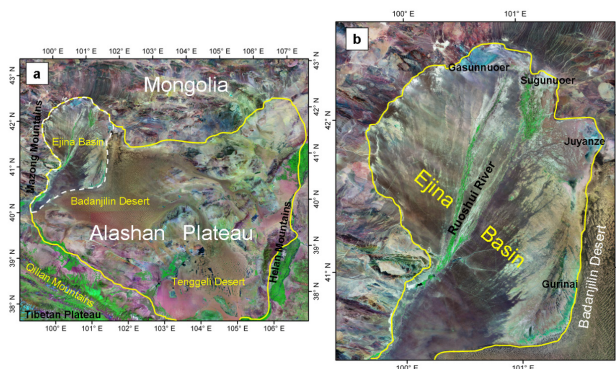


Figure 2. Overview remote-sensing images (Landsat TM, RGB 7-4-2) of the Alashan Plateau (a) and the Ejina Basin (b) (Cited from Zhu et al., ^[34]).

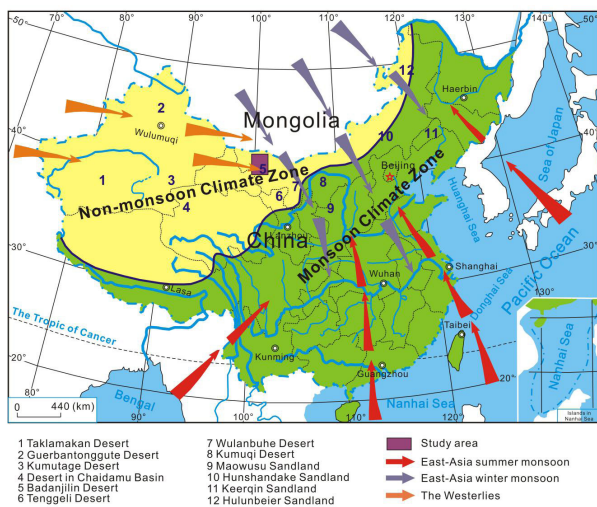


Figure 3. Distribution of deserts, monsoon zone and non-monsoon zone in China and the location of the Ejina Basin (modified from Zhu et al., ^[34])

2. Regional Setting and Methods

The Ejina Basin is located in the west part of the Alashan Plateau, between 40-43 ° N and 99-102 ° e (Figure 2, 3). The gravel plain of the Alsshan Gobi and the big sand sea of the Badanjilin Desert are adjacent to the basin in the north and East respectively (Figure 2). The Ejina basin is composed of three main sub-basins. When the Ejina River moves back and forth on its tail delta, these sub-basins are supplied by the river alternately. From west to East, these basins are the Gashunor Basin, the Sugunor Basin and the Juyanze Basin (Figure 2b).

At present, the climate of the Alashan Plateau belongs to extreme arid climate, with single hydrological environment. Only one river system (the Ejina River) is developed in the Ejina Basin ^[33]. The climate of Ejina Basin belongs to arid climate under desert conditions. In the past 50 years, the average annual temperature of Ejina is 8.8 ° C (Figure 4a), the maximum daily temperature is 41 ° C (July), and the minimum temperature is - 36.4 ° C (January). The annual average precipitation of the last 50 years recorded by the Ejina meteorological station is 35.6mm (Figure 4a). From the perspective of climate, the region can be divided into extreme drought ($120 > P > 60\text{mm}$) or drought ($60 > P > 30\text{mm}$) according to different sub-regions (perucca and Martos, 2012). The multi-year average prevailing wind comes from the west, and the northwest wind is almost common from August to September on the annual scale.

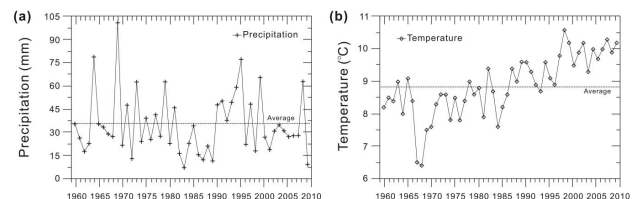


Figure 4. Variations of the average annual precipitation and temperatures (over 50 years during AD 1960-2010) in the Ejina Basin

In order to build a comprehensive database of geomorphological and climatic analysis in the Ejina Basin, we need to integrate data sets from wide different disciplines and use the technology of image processing and geographic information system (GIS) and the tools of spatial statistical analysis. Among these data sets, the geochronological analysis database (such as OSL and 14C dating data) comes from the domestic and foreign literatures on desert Research in China. Zhu et al. ^[34] conducted a geomorphological field survey in the whole Ejina Basin and partially described it. According to Landsat-ETM+ image data, topographic map and field investigation, they described

the geomorphological pattern of the basin and the geomorphological characteristics of special landforms in different types on different spatial scales in the Ejina Basin. They studied the sedimentary facies and shallow surface sedimentary profile in the middle, south and north parts of the Ejina Basin, and found out the specific combination of genetic related sedimentary facies, which provided the basis for the interpretation of sedimentary environment. For a detailed review of selected natural geomorphic elements, thematic maps of 1:500000 scale, topographic maps of 1:100000 scale and aerial and satellite photographs were used. Global positioning system (GPS) and Google Earth 1:50000 images were also used for field positioning. This paper focuses on the identification and investigation of the modern morphogenetic processes in the Ejina Basin, which is 980-2500 meters above sea level. The upper, middle and lower reaches of the Ejina River flowing from Langxinshan northwards to the Lake Sugunor (East Juyan sea) are investigated in detail. The geomorphological recognition and classification of landforms are mainly based on the system and principle of climate Geomorphology (for some details, see the literature^[34-35]). In the research work, the records of precipitation, temperature and wind on the annual, monthly and daily scales from 1960 to 2010 were collected from the Ejina meteorological station (subordinate to the Ejina Qi Meteorological Bureau) in the middle part of the Ejina Basin, which was used to explain the potential climatic and geomorphic processes or geomorphic background. In addition, combining with modern meteorological data of the Ejina Basin in recent decades, we have adopted some geomorphoclimatic models builded from the principles of climatic geomorphology to identify the modern dominant geomorphodynamics and related geomorphic processes occurred in the Ejina Basin. On the basis of this, the environmental indications of the modern and ancient climatic landforms in the Ejina Basin and the law of landform evolution are discussed.

3. Results and Discussion

3.1 Tectonic and Climatic Landforms in the Ejina Basin

Based on the major geomorphic types and geological structure, as well as the degree of structural stability, the application of geomorphic standards in deserts can generally be divided into shield / platform deserts and mountain / basin deserts^[36]. Shield desert is basically formed on cratonic terrane, which is basically formed by late Precambrian rocks and platforms with young age. They are characterized by flat terrain and are damaged by recent volcanic mountains and important faulting activities.

Mountain deserts are usually made up of long-distance mountain groups separated by lowlands^[36]. According to this definition, the Alashan Plateau deserts belong to mountain/basin desert. They are the marginal landforms of some highlands formed during the Mesozoic and Cenozoic alpine orogeny^[37]. Due to the topographical contrast and terrain difference, the high altitude areas are continuously eroded, and the formed materials are deposited in the form of coalescence alluvial fans in the depression lowlands or basins, such as the Ejina Basin (Figure 2).

Quantitative geomorphic information of the Alashan Plateau was previously extracted by researchers from digital elevation model^[19,34,37]. These studies reveal that the geomorphic types of landforms in the Alashan Plateau are neither uniform nor homogenic and there are systematic regional differences in the plateau, but on the whole, it presents a topographical pattern of south-higher-than-north and east-higher-than-west. Most areas of the plateau are characterized by positive terrain, that is, the terrain with positive correlation between elevation and relief, and average slope. Based on radar wave data and Landsat Image (TM, MSS) data, many ancient hydrological landforms such as river valleys and lake basins buried by aeolian sands were identified in the north of the Ejina Basin and the Alashan Plateau^[37]. The ancient hydrological system is in a NW-SE trend, which is obviously not in line with the present geomorphic pattern of south-higher-than-north and east-higher-than-west. This fact indicates that the neotectonic movement since Pleistocene may have caused a severe relief reversal in the Alashan Plateau.

On the Alashan Plateau, the topographical change in the Ejina Basin, especially along the Ejina River, is the largest in the whole plateau, because they span the margin zone of an ancient eroded plateau. This means that the topography of Ejina Basin is strongly controlled by the regional tectonic background. Except for the Ejina Basin, there is no continuous fluvial process in any other area of the Alashan Plateau (only confluence process of transient water flow and other hydrological processes exist locally,^[33]). This means that the current climatic and hydrological conditions in the Ejina Basin are relatively special, monotonous and stable under the plateau background. They constitute the main geomorphological processes and geomorphic forces of the Ejina Basin. Based on this point, we believe that the river system evolution at basin scale, the efficiency of water and sediment transport, the ability of river to transport sediments out of the Qilian Mountain, coupled with the large-scale climate change and tectonic-controlled topography, are the main mechanisms to explain the geomorphic differences in the Ejina Basin. It can be said that the process of basin sediment filling caused by

low efficiency of runoff conditions is smoothing and eliminating the tectonical relief of mountain desert system, which is the general trend of landform evolution in the Ejina Basin. On the other hand, it should be noted that the current smoothing model starts at the same time with the tectonic construction of the basin relief. The current geomorphic evolution of the Qilian Mountains in the north-east of the Qinghai Tibet Plateau is the clearest illustration of this model^[34].

Therefore, in terms of geomorphology, the topographic conditions of the Ejina Basin are diverse due to the co-existence of mountains, peneplain and basins, which are directly related to the formation of geomorphology related to geological processes such as structure, erosion, transportation and sedimentation^[33-34]. We can emphasize that the first-class landform of the basin is determined by regional lithologic geology and structural factors, which are obvious structural geomorphic dynamic process, showing obvious topographic gradient and terrain difference between the Qilian Mountain in the south, the Mazong Mountain in the West and the lake facies base basins in the East and the North (Figure 5).

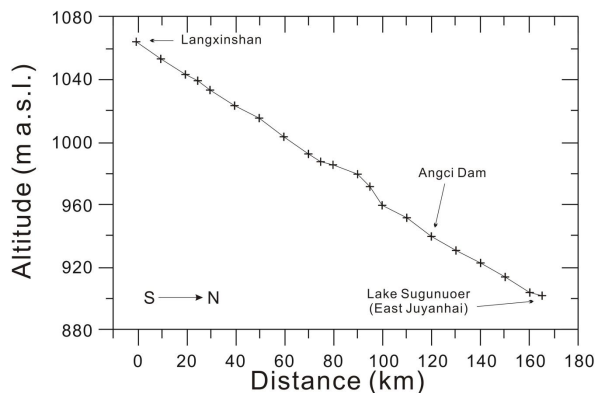


Figure 5. A topographical profile of the S-N trending line along the Ejina River from Langxinshan to Lake Sugunuoer

In addition to morphotectodynamic factors, satellite images and field investigations show that the Ejina Basin is located in the center of the arid area in northern China. Desert landscapes such as Gobi and aeolian sand dunes are the most widely distributed landforms here and even in northern China, which are obviously the fruit of climate factors, and therefore the most typical types of climate-driven landforms^[6-7, 34, 38-40]. In terms of climate geomorphology, the climate-driven landforms occurred in the Ejina Basin can be roughly divided into six types.

Desert plain, also known as “Gobi” or “gravel desert”, is a kind of landform controlled by aeolian dynamics and water dynamics and the interaction intensity between the

two dynamics is relatively equal. In terms of climate geomorphology, it is a typical landform with balance of wind and water forces^[38]. The energy of the geomorphodynamics that forms desert plain is usually low and the ideal precipitation required to form the landform is between 30-60 mm^[38]. Landforms of desert plain can be divided into two geomorphological types: the erosion-born type and the accumulation-born type. The accumulation type is close to the force of wind dynamics and the erosion type trends to the waterdynamics, such as peneplain or piedmont area^[38-39]. The typical landform of desert plain is distributed in a large area of the whole Ejina Basin from south to north (Figure 6). It is also known as the “Great Central Gobi” or “the Ejina Black Gobi”. The landform of desert plain in the Ejina Basin is mainly an accumulation-born type.

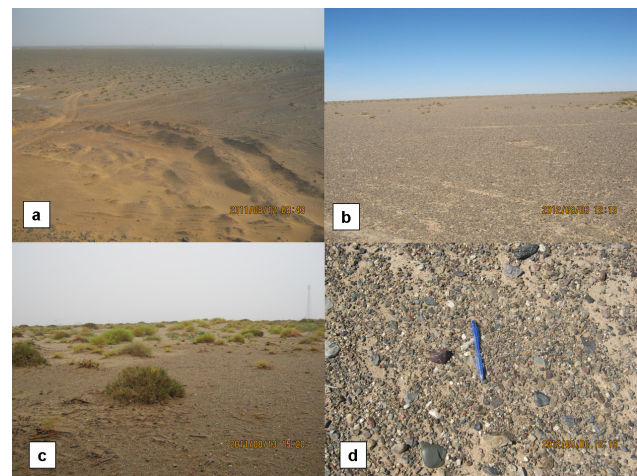


Figure 6. Landform of desert plains in the Ejina Basin

Pediment, one kind of the peneplain landform, is also a kind of landform in climatic origin^[35]. It is a conical relief characterized by a channel net, namely a landform being gently inclined with cone-shaped plane that characterized by the distribution of river grids on the slope. The formation of pediment is mainly controlled by the frost weathering and periglacial (ice-margin) processes^[38,41]. Pediment landform can be divided into two subtypes, the erosion-born type and the accumulation-born type, which usually occurs in piedmont and the front highland of desert plain^[38]. The climate conditions for forming pediment are cold climate with annual mean temperature $< -3^{\circ}\text{C}$ and annual mean precipitation between 150-300 mm^[38]. The key to the formation of pediment is to produce loose rock debris through the freeze-thaw and weathering processes, and the precipitation converges into slope flow and then transports these clastic sediments to river channel or the front of alluvial fan for deposition^[35,38]. The pediment landforms are mainly distributed in the western and northern edges of the Ejina Basin, the areas with higher eleva-

tion of piedmonts and desert plains (Figure 7).

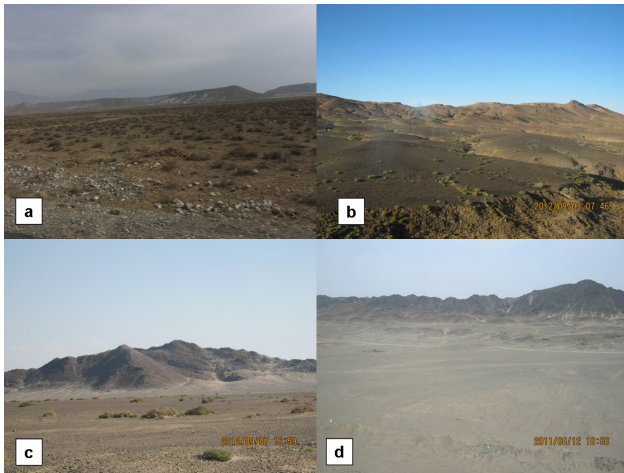


Figure 7. Landform of pediments in the Ejina Basin

Desert gorge or desert hill, is a landform which usually appears in the upper part of desert plain or piedmont. It is also a kind of climate landform formed by the transformation of tectonical landforms experienced the erosion and planation effects of the freeze-thaw, glacial and fluvial processes [38,41]. The environmental conditions for the formation of desert gorges are under the comprehensive effects of frost weathering and glaciation or fluvial processes, with annual mean precipitation between 100-300 mm [35,38]. The landform of desert gorges is widely distributed on the surrounding hillsides of the Mazong Mountains in the west of the Ejina Basin (Figure 8).

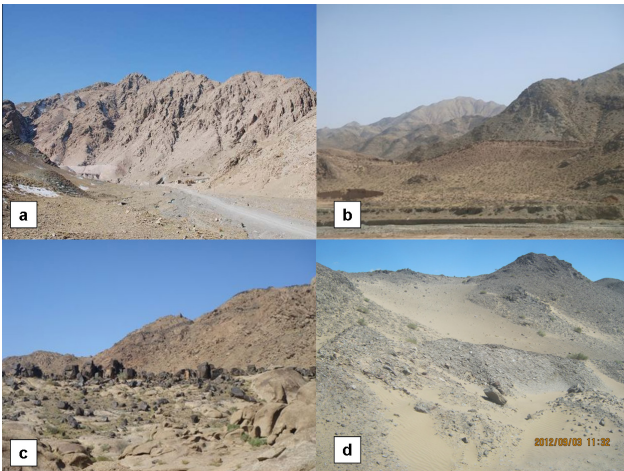


Figure 8. Landform of desert gorges in the Ejina Basin

Sandy dunes. In terms of climate geomorphology, sandy dune is a typical aerodynamic relief and an accumulation landform usually formed under arid environment with annual mean precipitation of less than 100 mm [35]. The main geomorphic forces forming this landform are wind (airflow or circulation), including aeolian (accumulation) and deflation (erosion) processes [38].

Therefore, sand dunes are regarded as a typical type of climate-driven landform [35]. Based on the theory of aeolian geomorphology, the formation of sandy dune landform in desert landscape is mainly controlled by several environmental factors. One is the stratification instability of the atmospheric boundary layer (i.e. the instability of troposphere thickness, the activity of near-groundsurface wind regime, and the high wind power or wind speed for sand-particle rising), the second is the foehn effect of dry radiabatic downdraft (i.e. drought conditions), the third is sufficient supply of sediment sources (sandy sediment availability), and the fourth is the uneven underlying surface conditions (a depositional environment of sediment accumulation rather than sediment erosion as formed by obstacles, so that sand dunes can be preserved). Identifying these factors is key to understand the formation of dune landform in desert landscape. The sand dune landform in the Ejina Basin is mainly distributed near the banks of the Ejina River (Figure 9), surrounded by Gobi (Figure 10). According to the vegetation-cover conditions, the dunes in the Ejina Basin can be divided into three sub-types: mobile dunes, semi-fixed dunes and fixed dunes (Figure 11). *Populus euphratica*, *Tamarix*, *Artemisia*, *Hippophae rhamnoides* and other plants are rarely distributed on the surface of sand dunes (Figure 9-11). Field investigation shows that the height of sand dunes changes regularly on the local scale, but the types of sand dunes in different places have little difference [33]. These three dune types are widely distributed and exist in any place of the basin.



Figure 9. Aeolian landform (dune fields) in the Ejina Basin. (a) Single dunes and dune chains, (b) sandy sheets, (c) and (d) Dunes accompanied by Tugai forests (*Populus euphratica*) and shrub vegetations (e.g., *Chionese tamarisk*) along the Ejina river banks

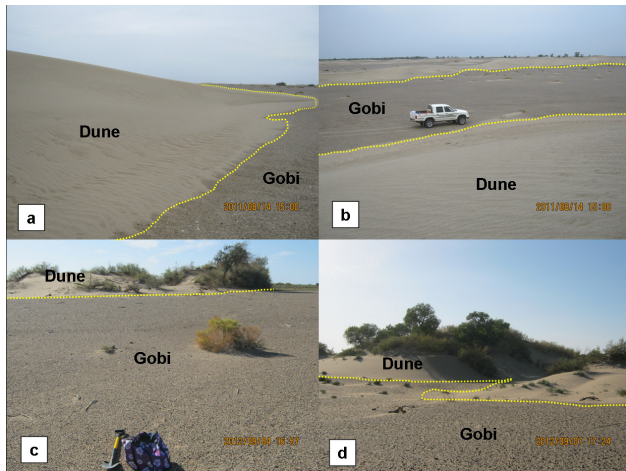


Figure 10. Active dunes developed on the Gobi deserts



Figure 11. Dune types in the Ejina Basin. (a) Active dune, (b) semi-active dune and (c) fixed dune

Fluvial and alluvial/proluvial landforms. These are typical hydrogenetic landforms controlled by river hydrodynamics and the hydroclimatic conditions of the drainage system. On the Alashan Plateau, the fluvial landform only exists in the Ejina Basin^[34], but the temporary alluvial/proluvial landforms occur in the pediment areas which locate widely in the northern Ejina Basin and the northern Alashan Plateau. In addition to the existence of modern river channels (Figure 12), many ancient river channels and alluvial fans can still be identified in the central part of the Ejina Basin from field investigations, historical maps and satellite images (Figure 2a). The Ejina River, also known as “Ruoshui River”, belongs to the lower reaches of the Heihe River, the second largest inland river of China, and is a unique river flowing through the Ejina Basin. The river originates from the Qilian Mountains and emerges at the Ejina Basin from its south corner (Langxinshan). The Ejina River runs northward about 160 kilometers and finally flows into the Sugunor Lake (also known as the East-Juyan-Sea) at the north end of the basin (Figure 5). As the general relief of the Ejina Basin is flat and wide relative to that of the Heihe River catchment, the area of alluvial/proluvial landforms in the Ejina Basin is generally smaller than other areas of the Heihe River Basin.



Figure 12. Fluvial landforms in the Ejina Basin. (a) A satellite image of the river channel (East River), gobi and dune distribution on a short section in the central part of the Ejina basin (form Google Earth), (b) wide and flat river channel (no water flowing by at the time), (c) sandy sedimentation in the riverbed, (d) intermittent flood discharge with muddy water derived from the Qilian Mountains

Lacustrine plain and playa landforms. No matter the alluvial/proluvial fan landform or lacustrine (lake) plain landform, they are all formed under the environment with better hydrological conditions. The formation of these landforms reflects that the initial climate is relatively humid and the river system is developed and the flood events are frequent. The landform of lacustrine plain is formed under the depositional environment with active water dynamics, while alluvial/proluvial fan is formed under the environment with static water dynamics. In the north of the Ejina Basin and the low reaches of the Ejina River, modern lake and playa basins are widely distributed (Figure 13). While in strata of the eastern and central Ejina Basin, deep lacustrine and marsh sedimentary layers are widely distributed, suggesting that lacustrine plain landforms existed in a large area of the Ejina Basin in the past. However, in the modern environment, the Ejina Basin has no hydroclimatic conditions for forming natural alluvial/proluvial plain and lacustrine plain, because the natural hydrological system has disappeared in the Ejina Basin and replaced by an artificially engineering hydrological system^[34].

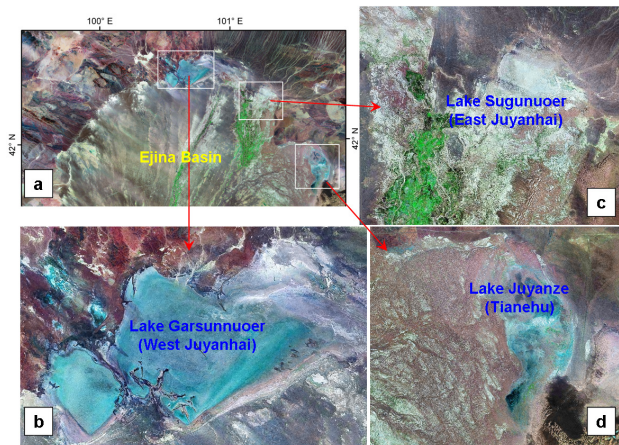


Figure 13. Overview remote-sensing images (Landsat TM, RGB 7-4-2) of the north part of the Ejina Basin (a), and the Lake Garsunnuoer (b), the Lake Sugunuoer (b) and the Lake Juyanze (d) in the Ejina Basin

3.2 Modern Geomorphodynamics and Morpho-climatic Processes in the Ejina Basin

In terms of climate geomorphology, there are many geomorphic models based on the theory of climate geomorphology, such as the Peltier model [42]. Combined with regional meteorological data, these models can be used to identify the relative importance of the main geomorphic dynamics and related geomorphological processes in an area. Peltier [42] uses the annual average temperature and rainfall data to define the semi-quantitative areas of frost/freezing strength and chemical weathering intensity, so as to define the frost and weathering dynamics and processes, respectively, as well as other dynamics such as gravity, glaciation, wind, pluvial erosion, fluvial and alluvial forces, etc., as shown in Figures 14-15. It has been reported that the simulated ranges of diverse geomorphodynamic regions superimposed on Peltier model map can prove the relative effectiveness of various geomorphic processes in arid and semi-arid environments, such as Mabbutt [36] and Gutierrez [35].

Applying the Peltier model to meteorological data such as annual mean temperature and precipitation over the past 50 years in the Ejina Basin, the Peltier model diagram states that:

The geomorphological system of the Ejina Basin is a geomorphoclimatic system from semi-arid type (less precipitation and moderate to warm) to arid type (less precipitation and cold to hot) types, which is dominated by physical processes and strong seasonality (Figure 14-15).

More than ten types of geomorphoclimatic forces that are common and recognizable in the world are distributed in Ejina Basin are as follows: the frost-freeze weathering

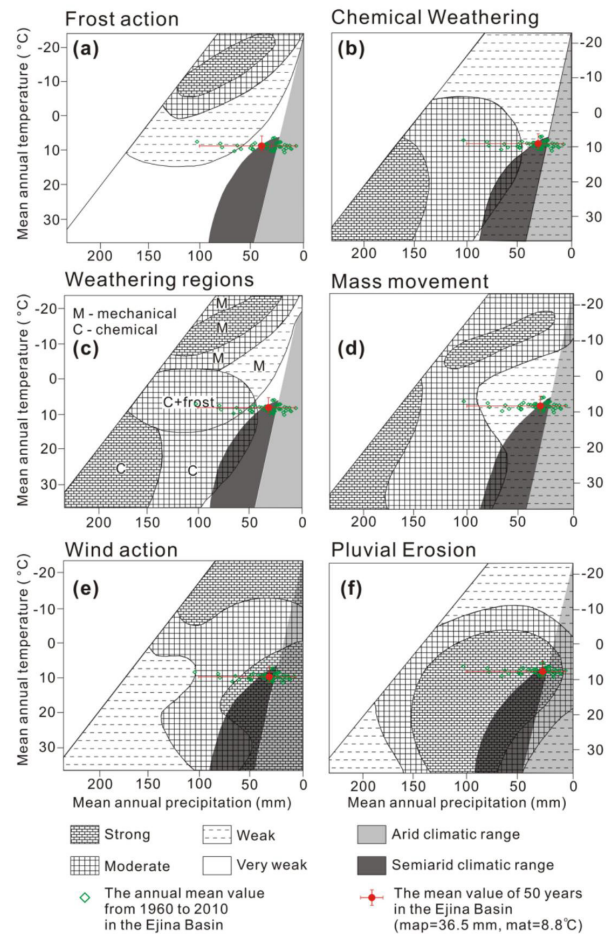


Figure 14. Effectiveness of landforming processes under different climatic conditions, related to arid and semiarid morphogenic regions. The basegraphs were after Peltier [42]

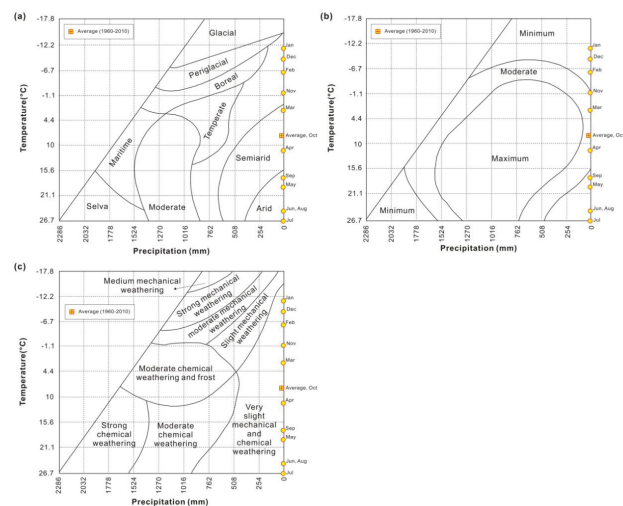


Figure 15. The affiliation of the characteristic months of the Ejina Basin. a To the morphogenetic regions, b to the intensity of fluvial action, c to the type and the intensity of the predominant processes in a Peltier diagram. The base-graphs were after Peltier [42]

is weak, the chemical weathering is weak, the comprehensive weathering (physi-chemical weathering) is weak, the gravity transportation is weak, the aeolian action/wind-accumulation is strong, the proluvial action (flood erosion) is strong, the fluvial forces such as rivers, lakes and mudflows are moderate and partially weak, no glaciation action, the periglacial action is weak, the frozen-soil action is weak, the desiccation-denudation (wind erosion) action is strong (Figures 14-15).

Summarizing the analysis results of the Peltier model map (Figures 14-15) and considering the modern climatic conditions, the main geomorphoclimatic dynamics with relatively strong power and energy are the processes of desiccation-denudation (wind erosion), eolian/wind-accumulation, and flood erosion in the Ejina Basin. In addition, there is a process with weak to medium power in the Ejina Basin, i.e. the fluvial forces. Other common geomorphoclimatic processes, such as frost/freezing and chemical weathering, are weak. The processes those related to glaciers, periglaciers, and frozen soils have little or no effect in the basin. In brief, the main geomorphic dynamics in the Ejina Basin are wind force and water force.

3.3 Interaction of Aeolian and Fluvial Processes in the Ejina Basin

When the average temperature of the coldest month in a desert area is generally lower than 0°C , it can be defined as a cold desert environment (relative to the hot and temperate desert environment) [43]. The most remarkable characteristics of this desert environment are the existence of huge thermal interannual oscillations. According to this standard, the Ejina environment belongs to a cold desert environment, because the average landsurface temperature of the coldest month in winter since 1965-2005 varies from -15°C to -25°C in the basin.

Based on the rules of occurrence of the significant landsurface processes and the dominant geomorphic types in the cold desert environment, we can identify the geomorphic processes in specific areas. Generally, two most important geomorphic processes can be identified in desert environment [44], one is dominated by wind dynamics and the other is dominated by water dynamics. This can be seen from the dominant types of the climate-driven landforms in the Ejina Basin that the aerodynamic and waterdynamic landforms coexist on a wide spatiotemporal scale in the Ejina Basin, so the two geomorphic dynamics may be superimposed in the Ejina Basin. Sedimentary records in the Ejina Basin can also prove this, such as the sedimentary sequences interbedding of eolian and fluvial sediments in stratigraphic profiles (Figure 14) and sand dune deposited along the riparian zone of the Ejina River

(Figure 9).

In geomorphology, typical aeolian landforms usually occur in areas with annual average precipitation less than 30 mm [38]. Dry climate promotes the development of mobile sand dunes, whereas these sand dunes become stable under humid conditions [38]. However, unlike the deserts in northern China, aeolian dunes in the Ejina Basin are mainly distributed on both sides of the river banks or nearby the river and the alluvial deposits, indicating that the formation of the aeolian landforms is largely affected by the fluvial or alluvial/proluvial process [33-34, 45]. A similar pattern of the sandy dune development was also observed in the Qaidam Basin [46]. The development of sand dunes along the Ejina River is abnormal because the river course and the surrounding areas are relatively humid but not dry. Regarding to the above-mentioned requirements for the formation of aeolian dunes in desert environment, as well as the fact that the landform in the central Ejina Basin is mainly Gobi landform with relatively flat terrain and consolidation of clastic sediments (that is to say, the process of wind erosion may be stronger than that of wind accumulation and the source of clastic material is deficient with sand sediment being not available) (Figure 6), the role of rivers on the development of sand dunes in the Ejina Basin may not inhibit the formation of aeolian dunes but provide the underlying uneven surface conditions and the potential source materials.

In the view of sedimentology, the riverbed surface sediments of the Ejina river is coarser downstream along the river channel [45], rather than finer downstream as other rivers in the world being [47-48]. Moreover, on the basin scale, the grain size of sand dune sediments in the Ejina Basin become finer gradually from south to north, which is consistent with the hydrological pattern of the basin, but not match to the composite direction of the prevailing wind system "from north to south" in the basin [33]. The sedimentological anomalies of fluvial and aeolian sediments on the spatial scale in the basin indicate an effective interaction and superposition effect of aeolian and hydraulic processes in shaping the basin landforms.

The above-mentioned geomorphological and sedimentological anomalies in the Ejina Basin indicate that the sediment supply of rivers and playas, the retation and blocking effect of river channels and related riverbank vegetation (such as *Populus euphratica*) on aeolian sediments, the relatively uneven underlying surface conditions built by river system and its weakening effect on local deflation process may be the key factors for the formation of sand dunes in the Ejina Basin, which may be even more important than the dry climate. In addition, the sedimentological changes of grain size of aeolian dunes

on the basin scale seem to be related to the local-scale factors such as hydrological processes in the Ejina Basin, but be decoupled with the regional-scale wind conditions. On the other hand, the temporary addition of aeolian sediments to the river sediments may be an important reason for the sedimentological anomaly of the downstream coarsening of river sediments along the Ejina River. It can be said that seasonal or transient rivers can be used as sediment interceptors to prevent the downwind movement of aeolian sediments. On the contrary, the aeolian sediment transportation can also affect the downstream distribution of river sediments. All of these indicate that there is a wide range of interaction between wind dynamics and water dynamics in the Ejina Basin.

It has been reported that in an arid environment, the interaction between aerodynamics and river dynamics can occur at the dune unit scale, the desert landscape scale or the watershed scale ^[49]. Especially at dune unit scale, the interaction between aerodynamics and river dynamics will affect the scope, shape and boundary of dunes field ^[50], as usual, the perennial river will directly restrict the downwind boundary of sand dunes development, while the temporary river will become the potential boundary of some sand seas. For example, the Orange River constrains the southwest boundary of dune downwind development in the southern Kalahari Desert in Africa ^[51], the Colorado River constrains the boundary of dune downwind development in the Algodones desert in Southern California of North America ^[52], and the dune range in northern Sudan of Africa ends on the Nile River ^[50]. The deserts bordered by temporary rivers are like the Wahiba Desert in North America, which ends at the intermittent wadi al batha River ^[53], and the Namib Desert in Central Africa, whose downwind desert edge ends at the Kuiseb river ^[50].

Regarding to the contact relationship between different sedimentary stratigraphic sequence and the upper and lower layers, as well as field investigation and remote sensing images (Figures 2, 6, 16), the desert plain (Gobi), as a main geomorphic unit in the central Ejina Basin, was transformed from the landform of alluvial/proluvial fans, which had originated from the alluvial/proluvial process of the Ejina river. As mentioned above, desert plain is a landform that has experienced the relatively balanced geomorphological processes between the wind dynamics and the water dynamics ^[38], and the ideal annual mean precipitation for the formation of desert plain is 30-60 mm. From this standard of climate geomorphology, the current climate conditions of the Ejina Basin are suitable for the formation and development of desert plain. Therefore, the Gobi landform should be a modern geomorphic type in the Ejina Basin. However, from the remote sensing image

(Figure 2), we can still recognize that there are large areas of alluvial fan landform in the basin, and there are also many residual landforms of riverbeds and river terraces. These mean that the Gobi landforms are still at the initial stage of its formation in the Ejina Basin.

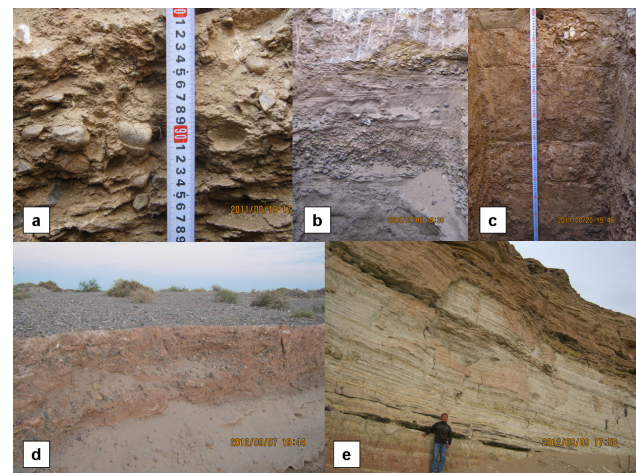


Figure 16. Sedimentary Profiles in the Ejina Basin: (a) proluvial-alluvial deposits (in desert plain), (b) complicated sedimentary sequence including sand, gravel, silt and clay sediments involved alluvial, fluvial, lacustrine and aeolian processes (in desert plain), (c) thick clayey deposits, (d) erosional terrace of river bank (margin of the basin), (e) palaeo-lacustrine section (at the low terrain of the north basin)

According to the contact relationship of stratigraphic layers, field observation and on-the-spot images, the formation of desert gorge landform is located at the upper part of the pediment and desert plain landforms in the Ejina Basin, and these gorge landforms often cut the mountain fronts (Figures 7, 8). Geomorphologically, the gorge and gully landforms are usually formed by the hydraulic process. Field investigation also confirmed this, because the signs of strong former erosion can be clearly observed on these landforms (Figure 8). In some places, loose sandy layers with unequal thickness have begun to cover the surface of these desert gorges. Geomorphologically, the formation of these sand layers should be aeolian origin and has experienced different degrees of desiccation-deflation processes due to drought conditions (Figure 8d). All these geomorphological evidences indicate that the aeolian and fluvial processes in the Ejina Basin are widely in progress.

3.4 Palaeo-environmental Indications of Landforms in the Ejina Basin

To understand the formation and evolution of landforms at different spatiotemporal scales in arid environment, on the one hand, it is necessary to identify the geomorphic

types and related morphogenetic and morphodynamic mechanisms, on the other hand, it is also dependent on whether good chronological data controlling the involved sedimentary events can be obtained for these landforms^[49]. Based on the climatic implications of different modern landforms and deposits, one can also estimate the past climate changes indicated by ancient landforms and deposits^[54], that is, to adopt the principle and method of “historical comparison” (namely that the present is the key to the past). For example, Hoevermann^[39] calculated the annual mean precipitation of the Qaidam Basin in the past 32 Ka, by comparing the annual sedimentation rate of clastic sediments in core CK 2022 from the central Qaidam Basin with that of modern lakes. Also, Goudie^[55] suggests that the area with the global largest frequency of duststorm at present or in the past is located in the area with rainfall between 100-200 mm/a, which is consistent with many modern observations from regions of Tibet, Mongolia and Africa^[38, 56-58].

3.4.1 Environmental Indications of Relict Landforms in the Ejina Basin

The climate prerequisite for the formation of a peneplain (pediment) landform is a cold winter and an annual mean precipitation of 150-300 mm^[38]. Of the great important for its morphogenetic mechanism is that the frost weathering in winter and the fluvial/alluvial/proluvial processes in summer are aligned with the formation of pediment. However, the current annual mean precipitation and temperature in the Ejina Basin are only 35 mm and 8.8 °C, respectively (Figure 4). Under the current climatic conditions, the process of desiccation-denudation (dry erosion) has dominated the whole year and only weak to moderate fluvial/alluvial/proluvial processes exist in the basin^[34]. Therefore, the current climatic and environmental conditions in the Ejina Basin can not form a real pediment landform.

The formation of the desert gorge landform in the Ejina Basin requires a strong erosion process of flowing water. The critical annual precipitation for the development of desert gorge landforms is considered to be 60-150 mm^[38]. But at present, the ground surface of these gorge landforms in the Ejina Basin is usually bare, and the current process of frost weathering is also weak due to lack of water. Therefore, similar to the pediment landform, the current Ejina Basin cannot form a true desert gorge landform due to water shortage.

According to Hoevermann^[38], whether it is desert gorge or pediment landform, the formation of both the two landforms reflects the existence of a climate that has more annual average precipitation and lower temperature

than the current. Therefore, the pediment and desert gorge landforms in the Ejina Basin are residual landforms (i.e. ancient landforms) related to the humid and cold climate in the past. At present, due to the prevalence of aerodynamic process and the existence of temporary fluvial/alluvial/proluvial processes, the pediment and desert gorge landforms are transforming into desert plains^[34]. In addition, the widespread occurrence of mobile sandy dunes and the presence of large-scale ancient lake beds indicate that the current drought index of the Ejina Basin is increasing^[34].

Landforms such as pediment and desert gorge in the Ejina Basin are also widely distributed in the northern, eastern and southern parts of the Alashan Plateau (Figures 2, 17) and in the desert regions in western China (Figure 1,^[34]). In view of the climatic geomorphology, the extreme arid and mid-latitude temperate climate backgrounds of the western China and the Alashan Plateau as a whole currently indicate that these landforms are residual landforms and are related to a humid and cold climate in the past. Geochronological studies from the lacustrine sedimentary sections in the central Alashan Plateau^[39-40] indicate that the Alashan Plateau was in a humid and cold climate during the local glacial maximum of the last glacial period, which is consistent with the environmental conditions required for the formation of pediment and desert gorges around the plateau. Field investigations show that the desert regions of western China have experienced obvious climate fluctuations in the Late Quaternary, accompanied by clear changes in landforms and paleohydrological environments^[7, 18-19, 54, 59-66]. Sand dunes and desert plain landforms are currently being formed in these areas, but the underlying residual landforms of desert gorges and alluvial fans should have been formed during the local glacial period^[6, 40]. Regarding to the comparability in geomorphology and sedimentology between different areas with similar hydroclimate (both arid areas), especially these areas have a similar low degree of weathering^[67], it may be logically reasonable to attribute the development age of the residual landforms such as desert gorges and pediments around marginal areas of the Ejina Basin to the local glacial maximum of the last glaciation. This idea is also supported by many sedimentary chronological data of similar arid areas. For example, studies have shown that during some glacial ages (approximately 32-24 ka) in Central Asia, northern China, Mongolia, and the Qinghai-Tibetan Plateau, the climate in these areas was more humid and cold^[2, 5-6, 10, 68]. Widely distributed residual ice wedges and moraine deposits in the Qaidam Basin and Tarim Basin of northwestern China indicate that the coldest period of the last glaciation in the two basins is

about 30-25 ka. Sequential sandy-dune sediments and high palaeo-lake levels in the Badanjilin Desert and its adjacent areas (such as Mongolia) indicate that the climate of north-central China and Mongolia during the marine oxygen isotope stage-three (MIS3) is much more humid than it is today ^[6]. The Loess Plateau of western China also had a cold and wet climate during MIS4 and MIS3 ^[5]. The north boundary of the Great Gobi in Mongolian has shrunk by nine times due to the humid climate in different periods of the past 40 ka, such as about 34.4ka, 30.7ka, 28.9ka, 24.5ka and 15.09 ^[71].

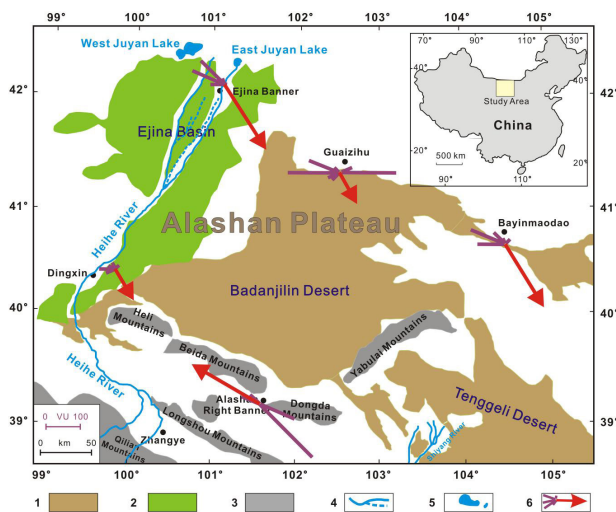


Figure 17. Landscapes of the Alashan Plateau (modified from Yang et al. 2011b). The compound directions of wind systems in different areas in the Alashan Plateau are also shown in the panel

Note: Legend 1 sand dunes, 2 fluvial/alluvial sediments associated with the Heihe River, 3 adjacent mountain ranges, 4 rivers, 5 lakes, and 6 sand roses (Fryberger and Dean 1979) for five surrounding weathering stations, with purple lines showing winds capable of transporting sand from various directions (DP, vector units with wind speed in knots VU) and red lines with arrows indicating the resultant sand transport trend (RDP, vector units in VU)

It has been reported that the marginal and central areas of the Alashan Plateau experienced a wide range of pedimentation processes during the last glacial period ^[39]. Researchers also identified three different stages of formation of pediment landforms at the foreland of the Qilian Mountains during the Pleistocene ^[39]. In view of the climatic geomorphology, the annual mean precipitation of these regions should be as high as 150-300 mm during the development of pediment landform. However, the current multi-year climate records from meteorological stations show that the annual mean precipitation in the southeast of the Alashan Plateau is only 110 mm, in the northwest is only 38 mm, and in the Ejina Basin is only about 36.5 mm (Figure 4a). Comparing the current climate of the Alashan Plateau with the corresponding climatic conditions when

the desert gorge landform (60-150 mm) and the pediment landform (150-350 mm) were formed, then the variation range of precipitation during the last glacial period in the Alashan Plateau should be at least 20-200 mm, which is much larger than the modern climate level; while the annual mean precipitation in the marginal areas of the Ejina Basin is about 60-350 mm during the LGM period, an increase of 50%-775 % than that today.

3.4.2 Environmental indications of modern landforms in the Ejina Basin

As mentioned above, the geomorphic types of desert plains (Gobi) and aeolian sandy dunes represent the landforms of modern origin in the Ejina Basin, because the current climate of the Ejina Basin match the environmental conditions for their formation and development in view of the climatic geomorphology. Under arid condition, the Gobi landform transformed from alluvial fans is a common phenomenon ^[69]. Evidences from stratigraphic profiles of remotely sensed images reveal that the Gobi landform in the Ejina Basin has also been extensively transformed from the original alluvial deposits (Figures 6, 16). Due to the reason that the formation of the Gobi landform requires a morphodynamic balance between aeolian and hydraulic processes, while the balance between these two dynamic factors cannot be simply explained by climate change in an arid environment because the results of climate change on the two agents are usually opposite, thus the adjustment and influence of tectonic activities must be considered. Therefore, reconstructing the evolutionary history of the Gobi landform is of great significance for revealing regional-scale tectonic activities and climate changes ^[5, 70-71]. In addition, the formation and evolution of alluvial fan are also closely related to regional tectonic activities and climate change ^[35]. In climatic geomorphology, sudden floods and strong winds are the two main driving factors for the formation of Gobi desert ^[35, 38]. As a result, the Gobi sediments experienced the processes of hydraulic transport and wind erosion and the related changes in tectonic activities and climate are also recorded. In genetics, the beginning of the development of a Gobi landform represents the end of the evolution of an alluvial fan ^[35].

The content of cosmogenic nuclide ¹⁰Be in the quartz gravel sediments on the Gobi surface in the Ejina Basin has been systematically measured ^[72-73] to evaluate the exposure age of these Gobi gravels. The results show that the exposed ages of the Gobi gravels in the northern edge of the Ejina Basin are more than 420 Ka, while those of the "Central Gobi" gravels in the Ejina Basin are 190 Ka (Figure 18). Judging from the spatial and temporal chang-

es of the ^{10}Be ages, the gravels in the Central Gobi gradually developed northward and eastward until the modern lake area at the end of the Ejina River. The spatiotemporal variation of the ages of the Gobi gravel outcrops in the Ejina Basin indicates that they are the result of the alluvial process influenced by the uplift and tectonic activities of the Qinghai-Tibet Plateau [73]. The ^{10}Be ages of the cosmic origin of the Gobi gravels indicate that the end of alluvial process and the beginning of the formation of Gobi landform in the northern edge of the Ejina Basin occurred before 420 Ka, while the formation of the Central Gobi in the Ejina Basin occurred before 190 Ka (Figure 18). The two critical periods are both in the glaciation ages of late Pleistocene.

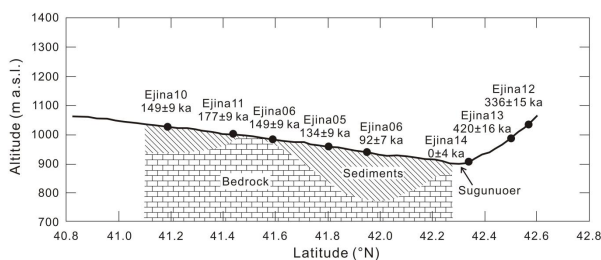


Figure 18. Variations in altitude, sediment thickness, and exposure ages of the quartz gravels from the Gobi deserts along a SW-NE transection in the Ejina Basin (after Zhang et al., [72] and Lv et al., [73])

The episodic formation of Gobi desert in the past 420 Ka indicates that the advance and retreat of alpine glaciers in glacial / interglacial cycles may be the main factors affecting the intensity of alluvial process and river water discharge in the Ejina Basin [72-73]. However, the strong proluvial (flooding) process and large amount of water could mainly occur in the short disglacial ages.

Since the formation and development of landforms between the Gobi and the alluvial fan have an inherited relationship in time, the source of sediments in the Gobi landform of the Ejina Basin may be closely related to ancient alluvial deposits, but not to modern river sediments. The differences in grain size sedimentology between the Gobi sediments in the Ejina Basin and the riverbed sediments from the Ejina Basin also show this point [45].

For arid intermountain basins in Central Asia, a large number of clastic sediments derived from alpine river transportation are stored in alluvial fan landform or become basin fillings [1-2]. The depositional process of alluvium is related to the land surface instability caused by regional climate change [35, 69]. It is worth noting that one of the landform characteristics of the Ejina Basin is its geomorphological instability under current climatic conditions [34]. For example, geomorphologically, the ancient alluvial fan landform in the Ejina Basin is changing

to desert plain landform, which can be proved by remote sensing images, the changes of sedimentary facies in the Gobi stratigraphic profiles, and the huge thickness of alluvial/proluvial strata widely distributed on the profiles (Figures 2, 16).

From the geomorphological perspective of the entire Central Asia, ancient alluvial fan landforms can be divided into two basic types: the decomposed alluvial fan and the undecomposed alluvial fan [74]. Most of the decomposed alluvial fans consist of relatively older surfaces (early to middle Pleistocene), while most of the undamaged alluvial fans have younger surfaces (late Pleistocene to Holocene) [74]. The distribution of alluvial fans formed in the Middle Pleistocene or earlier is relatively limited. Due to the relative uplift of the fan toes, the well preserved ancient alluvial fans are only limited to the area where the fan surface inclines rapidly toward the fan tip [75]. The alluvial fans at the southern margins of the Tarim Basin in Western China are typical examples of this type [74]. In the Ejina Basin, however, the ancient alluvial fan buried in the desert Gobi landform has hardly been destroyed. Through comparative analysis with the Tarim Basin, it can be considered that the alluvial fan landform of the Ejina Basin is younger than that of the Tarim Basin, and the alluvial fans in the Ejina Basin should have developed since the late Pleistocene. This is consistent with the ^{10}Be exposure ages of the Gobi gravels mentioned above.

3.4.3 Environmental Indications of Chronological Records in the Ejina Basin

Over the past decades, great progress has been made in geochronology of the Ejina Basin and the Aashan Plateau. For example, many studies have conducted geomorphological and chronological surveys on the three ancient lake basins in the Ejina Basin (Gashunuoer Lake Basin, Sugunuoer Lake Basin and Juyanze Basin). Evidences from studies of ancient lake shorelines and sedimentary cores of these lake basins indicate that these areas experienced severe environmental changes during the Holocene [76-78]. Almost all of these studies show that the climate fluctuated greatly during the Holocene in the Ejina Basin and in the Alashan Plateau [11, 79-84], which is related to the dynamic changes of the Asian monsoon or/and the westerly circulation flowing through China that follows the changing trend of the insolation patterns of northern hemisphere [10, 80].

The ancient river bed and ancient lake bed landforms in the Ejina Basin are numerous and can be identified from field observations or remotely sensed images (Figures 2, 13, 16). According to field investigations and the geomorphological mapping of the water level of the Sugunor Lake, we calculated that the high lakewater level of the

ancient Sugunor Lake was nearly 40 m above the current lakewater level. Investigations in the area of Guaizi Lake in the northern Badanjilin Desert show that there are three levels of high terraces on the south bank of the lake, and the highest terrace is about 40 meters higher than the modern lake bed. A survey at the Guinai Lake revealed that the ancient lake terrace in the southern part of the lake basin was more than 20 meters above the modern river bed. In previous studies, the height of lake bed of the Gashunor Lake is regarded as zero base level, then the highest terraces around the Sugunor Lake and the Juyanze Lake are 34 m and 33.6 m higher than the bed of Gashunor Lake, respectively^[85]. Since there is no bedrock mountain range between the Gashunor and sugunor lake basins, and there are lower terrain channels connecting the Juyanze lake basin and Sugunor lake basin, it can be reasonably assumed that in the past period with high lake levels, the water surfaces of the three lakes were connected together to form a whole. The radiocarbon age of the shell samples collected from the uppermost terrace of the Sugunor lake Basin showed that the sedimentary age was about about 33.7 Ka during the last glaciation^[85].

Studies have reported the results of geochronological analysis of sedimentary cores from the Gashunor and Sugunor lakes in the Ejina Basin^[76]. The geochronology data of these lakes are from 62 ¹⁴C dating results. In the areas of the Gashunorake and Sugunor lakes, the geological ages of the sedimentary terraces with the highest lakewater levels, which are about 28m to 32m above the modern lake bed, occur between 14 ka and 33 ka. The water levels of the Gashunnuo Lake dropped by about 15 meters and 18 meters at about 21 ka and 19 ka, respectively. After 19 ka, the areas of the Gashunnuor and Sugunuoer lakes were arid, and the sand dune sediments continued to be deposited until 14 ka. In addition, no dating data and materials were available between 18.6 Ka and 12.8 Ka. This phenomenon supports the state of aridity during this period, because the lacustrine sedimentation process in an arid environment will lack organic matter and thus radiocarbon dating materials, resulting in the discontinuous chronological data. After 11.3 ka, a freshwater lake appeared in the areas of the Gashunor and Sugunor lakes.

The ancient Juyanze Lake in the eastern Ejina Basin (Figure 13d) (41.75-42°N, 101.5-102°E) provides evidence of the complex hydrological pattern in the area in the Holocene^[86]. The lithology, geochemistry and mineralogy data of the lake's sedimentary core show that there are significant differences between the lakes in the early, middle and late Holocene. During the period of about 10,700 cal BP, the lake began to become a fresh water lake, formed in the regional extreme runoff events affect-

ed by humid climate. During the period of about 8900 to 8100 cal BP, the runoff in this lake area was very small. Compared with the humid climate in the early Holocene, the rainfall conditions from the middle to late Holocene are not obvious, and it shows a general trend of drying up completely of the lake^[86].

3.5 The Conceptual Model Coupling Landform and Climate

Over the years, geomorphologists and paleoclimatologists have summarized the different geomorphological processes and different paleoclimatic evidences in the basins and mountain areas in Central Asia since the late Quaternary (the past 100000 years)^[6,54,58,63,87-88]. The relationship between these landforms and environmental changes is summarized into a conceptual model. The schematic diagram of the model is roughly shown in Figure 19. Among them, the climate fluctuations of glaciations are based on the research results of glaciers on the Tibetan Plateau^[2,54,87]. In the Qinghai Tibet Plateau and the surrounding mountainous areas, the expansion of the largest glaciers occurred during two stages of the last glaciation (i.e. MIS4 and MIS2 at about 70-50 Ka and 32-14 Ka, respectively, particularly the late glaciation at about 15 ka), and the expansions of these glaciers have promoted the development of desert gorge and pediment landforms in these areas^[87-87]. While during MIS 3, these areas were in a relatively humid climate because of the high water levels in some lakes. Overall, the establishment of this conceptual model, which couples the landforms and climatic environment in Central Asia since the late Pleistocene, provides an important clue for understanding the relationship between landforms development and climate fluctuations in the Ejina Basin since the last glacial period under a large-scale background.

The wide distribution of the Gobi desert landforms in Central Asia is mainly derived from alluvial fan landforms and pediment landform with fanglomerates accumulation. As shown in Figure 19, there is a transition from humid (mainly MIS3) to arid climate in most parts of Central Asia. The observation of Late Quaternary alluvial fans in the Gobi deserts, southern Mongolia, indicates that there may be more humid conditions between 40-23 Ka, followed by a dryer period^[63]. The highest water level (28-32 m) in the past occurred between 41 and 33 ka in the Gashunnuoer-Sugunuoerhu lake area of the Ejina Basin^[76,85]. Compared with the climate of the Ejina Basin today, the appearance of these high lake water levels should be related to the high palaeo-precipitation and palaeo-hydrological cycle in the past.

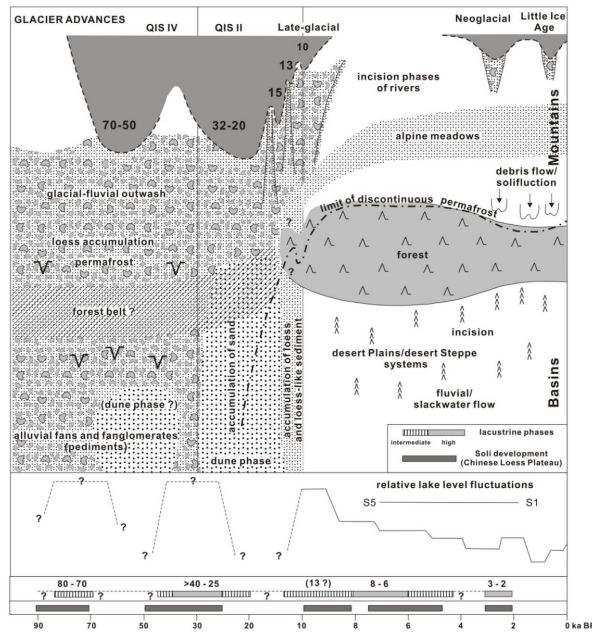


Figure 19. A conceptual model of Landform and climate in central Asia including lake level changes, glacier fluctuations in the mountains (top) and basins (bottom) of northern China and Mongolia during the late Pleistocene (Modified from [54,88])

In terms of climate genesis, the increase of precipitation in western Inner Mongolia (including the Alashan Plateau and the Ejina Basin) during the last glacial period may be due to the enhanced westerly circulation [6]. Benn and Owen [87] also suggested that glaciers in the northern Tibetan Plateau and northern Karakoram also responded to changes in the westerly circulation during the late Pleistocene. The humid climate in western Inner Mongolia during the Anaglacial period (about 32-24 ka) may be caused by the enhancement of the Westerly circulation and the weakening of the Winter Monsoon Circulation [54]. The changes of the two circulation systems both influence the western region of Central Asia first, while the latter (winter monsoon) affects mainland China and eastern Central Asia. The drought in western Inner Mongolia during the Kataglacial period (approximately 24-15 ka) may be due to the great movement of the Siberian High to the south and the strengthening of the Winter Monsoon, which led to arid climate in northern and central China [90-92]. Therefore, the different climate changes during the glacial period in western Inner Mongolia, especially the changes in precipitation, may be mainly affected by changes in the Siberian high-pressure system and its thermal effects. The persistent enhancement of the Siberian high in winter and spring may significantly increase the gradients of the wind and temperature fields in the surrounding area; while the relatively weak and northward contraction of Sibe-

rian high system will increase the cyclonic precipitation brought by Westerly circulation or/and monsoon circulation in spring, resulting in the humid climate in Central Asia.

The high lake level is evidence of a relatively humid climate in the early Holocene in the central Alashan Plateau [6, 40]. However, the pollen data records of the core of Lake Sugunor in the Ejina Basin did not show that the area was the wettest in the early Holocene [93]. The results of these studies indicate that the water supply in the arid area of Inner Mongolia during the Holocene period may be very unstable or has obvious regional differences. Because the East Asian Summer Monsoon circulation interacts with the Westerly circulation at the northern boundary of the summer monsoon, variations between dry and wet climate conditions in western Inner Mongolia may be more pronounced than other regions in China controlled by monsoon climate.

4. Conclusion

The formation of landforms on earth mainly depends on internal and external forces. The internal force, especially the tectonic movements since the Mesozoic and Cenozoic, are the overall constraints of the current mountain-basin coupling landforms in the Ejina Basin and even the Alashan Plateau. The external force is mainly controlled by climatic factors, which is the main reason for the geomorphodiversity of the Ejina Basin. Desert plain (Gobi), pediment, desert gorge, aeolian dune, fluvial channel and ancient lacustrine plain are the main existing geomorphic units in the basin. This study shows that there is a close relationship between the geomorphoclimatic processes and the landforms in the Ejina Basin. From the perspective of climate geomorphology, the existence of peneplain (pediment) landform shows that the study area has experienced high precipitation and frost/freezing and weathering process, that is, there was a humid and cold climate. The landform of desert gorges on the edge of the basin is an ancient landform eroded by running water or melting water. Flood erosion and wind action are the main geomorphic dynamics in the basin under the present climate. They are also the main geomorphodynamics for the formation of the Gobi desert landform. Aerodynamic and Gobi landforms usually occur in areas where the annual mean precipitation is less than 30-60 mm. Small sandy dunes are widely distributed along the Ejina River, and the Gobi desert landform is the main geomorphic type in the central basin. At present, the average annual precipitation in the Ejina Basin is about 35mm, indicating that the landforms of desert plain and aeolian dune are contemporary landforms that match the current climate. The existence of ancient landforms such as pediment and desert gorge

indicates that the range of precipitation variation in the past has reached 20 to 200 mm, which is much greater than the current climate level. The coexistence of these ancient landforms and contemporary landforms shows that the diversity of basin landforms is the result of the joint effect of tectonic activities, freeze-thaw and weathering, fluvial, alluvial/proluvial and aeolian processes, as well as climate change. Previous evidences have proved that the geomorphology of Central Asia is mainly the result of Quaternary climate change, which has forced changes in the environment of piedmont regions and basins. The landform evolution of the Ejina Basin further confirmed this, and the geomorphological evolution of the Ejina Basin since the late Pleistocene has been greatly influenced by external forces (climate). The study of the ancient lake geomorphology and sedimentation in the lowest marginal area of the basin shows that the arid environment in the region has changed drastically since the last glacial period. It experienced a humid climate and high precipitation at 39-23 ka BP and obvious climate fluctuations during the Holocene. Due to the relatively weak Asian summer monsoon in the glacial period, the changes in the Westerly circulation during the late Pleistocene and the regulation of the Siberian high system may be the main factors affecting the climate change in the Ejina Basin and in the entire Alashan Plateau.

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References

- [1] Liu, T., Ding, M., Derbyshire, E.. Gravel deposits on the margins of the Qinghai-Xizang Plateau, and their environmental significance. *Palaeogeography Palaeoclimatology Palaeoecology*, 1996, 120: 159-170.
- [2] Liu, T., Zhang, X., Xiong, S., Qin, X., Yang, X.. Glacial environments on the Tibetan Plateau and global cooling. *Quaternary International*, 2002, 97-98: 133-139.
- [3] Liu, T., Ding, Z.. Chinese loess and the paleomonsoon. *Annual Review of Earth and Planetary Sciences*, 1998, 26: 111-145.
- [4] Sun, J., Ding, Z., Liu, T.. Desert distributions during the glacial maximum and climatic optimum: example of China. *Episodes*, 1998, 21: 28-31.
- [5] Feng, Z., Chen, F., Tang, L., Kang, J.C.. East Asian monsoon climates and Gobi dynamics in marine isotope stages 4 and 3. *Catena*, 1998, 33: 29-46.
- [6] Yang, X., Rost, K.T., Lehmkuhl, F., Zhu, Z., Dodson, J.. The evolution of dry lands in northern China and in the Republic of Mongolia since the Last Glacial Maximum. *Quaternary International*, 2004, 118-119: 69-85.
- [7] Yang, X., Scuderi, L. A., Paillou, P., Liu, Z., Li, H., Ren, X.. Quaternary environmental changes in the drylands of China: a critical review. *Quaternary Science Reviews*, 2011, 30: 3219-3233.
- [8] Yang, X., Li, H., Conacher, A.. Large-scale controls on the development of sand seas in northern China. *Quaternary International*, 2012, 250, 74-83.
- [9] Ding, Y., Chan, J.C.L.. The East Asian summer monsoon: an overview. *Meteorology and Atmospheric Physics*, 2005, 89: 117-142.
- [10] Herzschuh, U.. Palaeo-moisture evolution in monsoonal Central Asia during the last 50,000 years. *Quaternary Science Reviews*, 2006, 25: 163-178.
- [11] Wünnemann, B., Hartmann, K., Janssen, M., Zhang, H.C.. Responses of Chinese desert lakes to climate instability during the past 45,000 years. *Developments in Quaternary Science*, 2007, 9: 11-24.
- [12] Stevens, T., Lu, H., Thomas, D.S.G., Armitage, S.J.. Optical dating of abrupt shifts in the Late Pleistocene East Asian monsoon. *Geology*, 2008, 36: 415-418.
- [13] Yang, S.L., Ding, Z.L.. Advance-retreat history of the East-Asian summer monsoon rainfall belt over northern China during the last two glacial-interglacial cycles. *Earth and Planetary Science Letters*, 2008, 274: 499-510.
- [14] Yang, S.L., Ding, Z.L., Li, Y.Y., Wang, X., Jiang, W.Y., Huang, X.F.. Warming-induced northwestward migration of the East Asian monsoon rain belt from the Last Glacial Maximum to the mid-Holocene. *Proceedings of the National Academy of Sciences of the United States of America*, 2015, 112: 13178-13183.
- [15] Mason, J.A., Lu, H., Zhou, X., Miao, X., Swinehart, J.B., Liu, Z., Goble, R.J., Yi, S.. Dune mobility and aridity at the desert margin of northern China at a time of peak monsoon strength. *Geology*, 2009, 37: 947-950.
- [16] Lu, H., Mason, J. A., Stevens, T., Zhou, Y., Yi, S., Miao, X.. Response of surface processes to climatic change in the dunefields and Loess Plateau of North China during the late Quaternary. *Earth Surface Processes and Landforms*, 2011, 36: 1590-1603.
- [17] Li, Q., Wu, H., Yu, Y., Sun, A., Markovic, S. B., Guo, Z.. Reconstructed moisture evolution of the deserts in northern China since the Last Glacial Maximum and its implications for the East Asian Summer Monsoon.

- Global and Planetary Change, 2014, 121: 101-112.
- [18] Yang, X., Scuderi, L.A.. Hydrological and climatic changes in deserts of China since the late Pleistocene. *Quaternary Research*, 2010, 73: 1-9.
- [19] Yang, X., Scuderi, L., Liu, T., Paillou, P., Li, H., Dong, J., Zhu, B., Jiang, W., Jochems, A., Weissmann, G.. Formation of the highest sand dunes on Earth“, *Geomorphology*, 2011, 135: 108-116.
- [20] Yang, X., Wang, X., Liu, Z., Li, H., Ren, X., Zhang, D., Ma, Z., Rioual, P., Jin X., Scuderi, L.. Initiation and variation of the dune fields in semi-arid northern China - with a special reference to the Hunshandake Sandy Land, Inner Mongolia. *Quaternary Science Reviews*, 2013, 78: 369 - 380.
- [21] Scuderi, L., Weissmann, G., Kindilien, P., Yang, X.. Evaluating the potential of database technology for documenting environmental change in China's deserts. *Catena*, 2015, 134: 87-97.
- [22] Guo, Z.T., Ruddiman, W.F., Hao, Q.Z., Wu, H.B., Qiao, Y.S., Zhu, R.X., Peng, S.Z., Wei, J.J., Yuan, B.Y. and Liu, T.S.. Onset of Asian desertification by 22 Myr ago inferred from loess deposits in China. *Nature*, 2002, 416: 159-163.
- [23] Sun, J.. Provenance of loess material and formation of loess deposits on the Chinese Loess Plateau. *Earth and Planetary Science Letters*, 2002, 203: 845-859.
- [24] Panizza, M.. The geomorphodiversity of the Dolomites (Italy): a key of geoheritage assessment. *Geoheritage*, 2009, 1: 33-42.
- [25] Testa, B., Aldighieri, B., Bertini, A., Blendinger, W., Caielli, G., de Franco, R., Giordano, D., Kustatscher, E.. Geomorphodiversity of the San Lucano Valley (Belluno Dolomites, Italy): a well-preserved heritage. *Geoheritage*, 2013, 5: 151-172.
- [26] Gordon, J.E., Barron, H.F., Hansom, J.D., Thomas, M.F.. Engaging with geodiversity why it matters. *Proceedings of the Geologists' Association*, 2012, 123: 1-6.
- [27] Beggs, P.J.. New directions: climatediversity: a new paradigm for climate science“, *Atmospheric Environment*, 2013, 68: 112-113.
- [28] Wang, X., Hua, T., Zhang, C.. Aeolian salts in Gobi deserts of the western region of Inner Mongolia: Gone with the dust aerosols. *Atmospheric Research*, 2012, 118: 1-9.
- [29] Natsagdorj, L., Jugder, D., Chung, Y.S.. Analysis of dust storms observed in Mongolia during 1937-1999. *Atmospheric Environment*, 2003, 37: 1401-1411.
- [30] Wang, X., Zhou, Z., Dong, Z.. Control of dust emissions by geomorphic conditions, wind environments and land use in northern China: An examination based on dust storm frequency from 1960 to 2003. *Geomorphology*, 2006, 29: 292-308.
- [31] Wang, X., Xia, D., Wang, T.. Dust sources in arid and semiarid China and southern Mongolia: Impacts of geomorphologic setting and surface materials“, *Geomorphology*, 2008, 97: 583-600.
- [32] Liu Z.J., Tapponnier, P., Gaudemer, Y., Ding, L.. Quantifying landscape differences across the Tibetan plateau: implications for topographic relief evolution. *Journal of Geophysical Research*, 2008, 113: F04018. DOI: 10.1029/2007JF000897
- [33] Zhu, B., Yu, J., Rioual, P., Ren, X.. Particle size variation of aeolian dune deposits in the lower reaches of the Heihe River basin, China. *Sedimentary Geology*, 2014, 301: 54-69.
- [34] Zhu, B., Yu, J., Rioual, P., Gao Y., Zhang, Y., Min, L.. Geomorphoclimatic characteristics and landform information in the Ejina Basin, Northwest China. *Environmental Earth Sciences*, 2015, 73: 7547-7560.
- [35] Gutierrez, M.. *Climatic Geomorphology*. Amsterdam, Elsevier, 2005.
- [36] Mabbutt, J.A.. *Desert Landforms*“, Cambridge, MA, The MIT Press, 1977.
- [37] Guo, H., Liu, H., Wang, X., Shao, Y., Sun, Y.. Sub-surface old drainage detection and paleoenvironment analysis using spaceborne radar images in Alxa Plateau. *Science in China Series D*, 1977, 43: 439-448.
- [38] Hoevermann, J.. Das System der klimatischen Geomorphologie auf landschaftskundlicher Grundlage. *Zeitschrift fur Geomorphologie Neue Folge*, 1985, 56 (Supplementary Band): 143-153.
- [39] Hoevermann, J., Hoevermann, E., Lehmkuhl, F. Geomorphologische Untersuchungen im noerdlichen Vorland des Qilian Shan, China. *Berliner geographische Abhandlungen*, 1998, 63: 83-98.
- [40] Yang, X.. Late Quaternary evolution and paleoclimates, western Alashan Plateau, Inner Mongolia, China. *Zeitschrift fur Geomorphologie Neue Folge*, 2001, 45: 1-16.
- [41] Mensching, H.G.. Inselberge, Pedimente und Rumpflaechen im Sudan (Repubhk) - Ein Beitrag zur morphogenetischen Sequenz in den arid Subtropen und Tropen Afrikas. *Zeitschrift fuer Geomorphologie*, 1978, 30 (Supplementband): 1.
- [42] Peltier, L.C.. The geographic cycle in periglacial regions as it is related to climatic geomorphology. *Annals of the Association of American Geographers*, 1950, 40: 214-236.
- [43] Meigs, P.. The world distribution of arid and semiarid homoclimates. *RivIEWS of Research on Arid Zone Hydrology*, Paris, UNESCO, 1953: 203-209.
- [44] Cooke, R.U., Warren, A., Goudie, A.. *Deserts Geomorphology*. London, UCL Press, 1993.

- [45] Zhu, B., Yu, J.. Aeolian sorting processes in the Ejina desert basin (China) and their response to depositional environment. *Aeolian Research*, 2014, 12: 111-120.
- [46] Yu, L., Lai, Z., An, P., Pan, T., Chang, Q.. Aeolian sediments evolution controlled by fluvial processes, climate change and human activities since LGM in the Qaidam Basin, Qinghai-Tibetan Plateau. *Quaternary International*, 2015, 372: 23-32.
- [47] Ferguson, R., Hoey, T., Wathern, S., Werritty, A.. Field evidence for rapid downstream fining of river gravels through selective transport. *Geology*, 1996, 24: 179-182.
- [48] Frings, R.M.. Downstream fining in large sand-bed rivers. *Earth-Science Reviews*, 2008, 87: 39-60.
- [49] Tooth, S.. Arid geomorphology: investigating past, present and future changes. *Progress in Physical Geography*, 2007, 31: 319-335.
- [50] Bullard, J.E., Mctainsh, G.H.. Aeolian-fluvial interactions in dryland environments: examples, concepts and Australia case study. *Progress in Physical Geography*, 2003, 27: 471-501.
- [51] Thomas, D.S.G., Stokes, S., Shaw, P.A.. Holocene aeolian activity in the southwestern Kalahari Desert, southern Africa: significance and relationships to late-Pleistocene dunebuilding events. *The Holocene*, 1997, 7: 273-81.
- [52] Sweet, M.L., Nielson, J., Havholm, K., Farrelley, J.. Algodones dunefield of southern California: a case history of a migrating modern dunefield. *Sedimentology*, 1988, 35: 939-52.
- [53] Warren, A.. The dunes of the Wahiba Sands. Special Report 3: the Scientific Results of the Royal Geographical Society's Oman Wahiba Sands Project 1985-1987. *Journal of Oman Studies Special Report*, 1988, 3: 131-60.
- [54] Lehmkuhl, F., Haselein, F.. Quaternary paleoenvironmental change on the Tibetan Plateau and adjacent areas (Western China and Western Mongolia). *Quaternary International*, 2000, 65/66: 121-145.
- [55] Goudie, A. S.. Dust storms in space and time. *Progress in Physical Geography*, 1983, 7: 503-530.
- [56] Hoevermann, J.. Morphogenetic regions in Northeast Xizang (Tibet). In, Hoevermann, J., Wang, W. (Eds.). *Reports of the Qinghai-Xizang (Tibet) Plateau*. Beijing, Science Press, 1987: 112-139.
- [57] Hoevermann, J., Lehmkuhl, F., Portge, K.H.. Pleistocene glaciations in eastern and central Tibet - Preliminary results of Chinese-German joint expeditions. *Zeitschrift fur Geomorphologie Neue Folge*, 1993, 92 (Supplementary Band): 85-96.
- [58] Lehmkuhl, F.. The spatial distribution of loess and loess-like sediments in the mountain areas of Central and High Asia. *Zeitschrift fur Geomorphologie Neue Folge*, 1997, 111 (Supplementary Band): 97-116.
- [59] Chen, K., Bowler, J.. Late Pleistocene evolution of salt lakes in the Qaidam Basin, Qinhai Province China. *Palaeogeography Palaeoclimatology Palaeoecology*, 1986, 54: 87-104.
- [60] Thompson, L.G., Mosley-Thompson, E., Davis, M. E., Bolzan, J. F., Dai, J., Yao, T., Gundestrup, N., Wu, X., Klein, L., Xie, Z.. Holocene-Late Pleistocene climatic ice core records from the Qinghai-Tibetan Plateau. *Science*, 1989, 246: 474-477.
- [61] Fang, J. Q.. Lake evolution during the past 30,000 years in China, and its implications for environmental change. *Quaternary Research*, 1991, 36: 27-60.
- [62] Li, S., Shi, Y.. Glacial and lake fluctuations in the area of West Kunlun mountains during the last 45,000 years. *Annals of Glaciology*, 1992, 16: 79-84.
- [63] Owen, L.A., Windley, B.F., Cunningham, W.D., Badamgarov, G., Dorjnamjaa, D.. Quaternary alluvial fans in the Gobi of southern Mongolia: evidence for neotectonics and climate change. *Journal of Quaternary Science*, 1997, 12: 239-252.
- [64] Zhang, H., Ma, Y., Wunnemann, B., Pachur, H.. A Holocene climatic record from arid northwestern China. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 2000, 162: 389-401.
- [65] Ye, W., Ji, F.. Comparison of paleoclimatic characteristics between monsoon and westerly areas, China. *Chinese Science Bulletin*, 2001, 46 (Supplementary): 119-124.
- [66] Yang, X., Liu, T., Xiao, H.. Evolution of megadunes and lakes in the Badain Jaran Desert, Inner Mongolia, China during the last 31,000 years. *Quaternary International*, 2003, 104: 99-112.
- [67] Zhu, B., Yang, X.. Chemical Weathering of Detrital Sediments in the Taklamakan Desert, Northwestern China. *Geographical Research*, 2009, 47: 57-70.
- [68] Mischke, S., Herzschuh, U., Zhang, C., Bloemendal, J., Riedel, F.. A Late Quaternary lake record from the Qilian Mountains (NW China): lake level and salinity changes inferred from sediment properties and ostracod assemblages. *Global and Planetary Change*, 2005, 46: 337-359.
- [69] Goudie, A. S.. Global deserts and their geomorphological diversity. In, Parsons, A.J., Abrahams A.D., (Eds.). *Geomorphology of Desert Environments*. Springer Science + Business Media, 2009: 9-20.
- [70] McFadden, L.D., Wells, S.G., Jercinovich, M.J.. Influences of eolian and pedogenic processes on the origin and evolution of desert pavements. *Geology*, 1987, 15: 504-508.

- [71] Feng, Z.. Gobi dynamics in the Northern Mongolian Plateau during the past 20,000+ yr: preliminary results. *Quaternary International*, 2001, 76/77: 77-83.
- [72] Zhang, H., Ming, Q., Lei, G., Zhang, W., Fan, H., Chang, F., Wunnemann, B., Rtmann, K.. Dilemma of dating on lacustrine deposits in a hyperarid inland basin of NW China. *Radiocarbon*, 2006, 48: 219-226.
- [73] Lv, Y., Gu, Z., Ala, A., Zhang, H., Goran, P., Lei, G.. ¹⁰Be in quartz gravel from the Gobi Desert and evolutionary history of alluvial sedimentation in the Ejina Basin, Inner Mongolia, China. *Chinese Science Bulletin*, 2010, 55: 3802-3809.
- [74] XETCAS (Xinjiang Expedition Team of the Chinese Academy of Sciences), IGCAS (Institute of Geography of the Chinese Academy of Sciences), DGBNU (Department of Geography of Beijing Normal University). *Geomorphology in Xinjiang*. Beijing, Science Press, 1978 (in Chinese).
- [75] Oguchi, T., Saito, K., Kadomura, H., Grossman, M.. Fluvial geomorphology and paleohydrology in Japan. *Geomorphology*, 2001, 39: 3-19.
- [76] Wunnemann, B., Pachur, H., Li, J., Zhang, H.. The chronology of Pleistocene and Holocene lake level fluctuations at Gaxun Nur/Sogu Nur and Baijian Hu in Inner Mongolia, China. *Petermanns Geographische Mitteilungen*, 1998, 142: 191-206.
- [77] Jin, M., Li, G., Li, F., Duan, Y., Wen, L., Wei, H., Yang, L., Fan, Y., Chen, F.. Holocene shorelines and lake evolution in Juyanze Basin, southern Mongolian Plateau, revealed by luminescence dating. *The Holocene*, 2015, 25: 1898-1911.
- [78] Li, G., Jin, M., Duan, Y., Madsen, D.B., Li, F., Yang, L., Wei, H., Chen, F.. Quartz and K-feldspar luminescence dating of a Marine Isotope Stage 5 megalake in the Juyanze Basin, central Gobi Desert, China. *Palaeogeography Palaeoclimatology Palaeoecology*, 2015, 440: 96-109.
- [79] Chen, F., Wu, W., Holmes, J.. A mid-Holocene drought interval as evidenced by lake desiccation in the Alashan Plateau, Inner Mongolia China. *Chinese Science Bulletin*, 2003, 48: 1401-1410.
- [80] Chen, F., Yu, Z., Yang, M.. Holocene moisture evolution in arid central Asia and its out-of-phase relationship with Asian monsoon history“, *Quaternary Science Reviews*, 2008, 27: 351-364.
- [81] Wunnemann, B., Hartmann, K., Altmann, N., Hambach, U., Pachur, H. J., Zhang, H.. Interglacial and Glacial fingerprints from lake deposits in the Gobi Desert, NW China. *Developments in Quaternary Sciences*, 2007b, 7: 323-347.
- [82] Yu, J., Kelts, K.R.. Abrupt changes in climatic conditions across the late-glacial/Holocene transition on the N.E. Tibet-Qinghai Plateau: Evidence from Lake Qinghai, China. *Journal of Palaeolimnology*, 2002, 28: 195-206.
- [83] Yu, Y., Yang, T., Li, J.. Millennial-scale Holocene climate variability in the NW China drylands and links to the tropical Pacific and the North Atlantic. *Palaeogeography Palaeoclimatology Palaeoecology*, 2006, 233: 149-162.
- [84] Zhang, H., Peng, J., Ma, Y.. Late quaternary palaeolake levels in Tengger Desert, NW China. *Palaeogeography Palaeoclimatology Palaeoecology*, 2004: 211, 45-58.
- [85] Norin, E.. *Sven Hedin Central Asia Atlas. Memoir on maps*, Stockholm, 1980.
- [86] Hartmann, K., Wunnemann, B.. Hydrological changes and Holocene climate variations in NW China, inferred from lake sediments of Juyanze palaeolake by factor analyses. *Quaternary International*, 2009, 194: 28-44.
- [87] Benn, D., Owen, L.. The role of the Indian summer monsoon and the mid-latitude westerlies in Himalayan glaciation: review and speculative discussion. *Journal of Geological Society London*, 1998, 155: 353-363.
- [88] Grunert, J., Lehmkuhl, F., Walther, M.. Palaeoclimatic evolution of the Uvs Nuur basin and adjacent areas (Western Mongolia). *Quaternary International*, 2000, 65/66: 171-192.
- [89] Yang, X., Preusser, F., Radtke, U.. Late Quaternary environmental changes in the Taklamakan Desert, western China, inferred from OSL-dated lacustrine and aeolian deposits. *Quaternary Science Reviews*, 2006, 25: 923-932.
- [90] An, Z., Wu, X., Lu, Y., Zhang, D., Sun, X., Dong, G., Wang, S.. Paleoenvironmental changes of China during the last 18,000 years. In: Liu, T. (Ed.). *Quaternary Geology and Environment in China*. Beijing, Science Press, 1991: 228-236.
- [91] Ding, Z., Liu, T., Rutter, N. W., Yu, Z., Guo, Z., Zhu, R.. Ice volume forcing of Asian winter monsoon variations in the past 800,000 years. *Quaternary Research*, 1995, 44: 149-159.
- [92] Pachur, H.J., Wunnemann, B., Zhang, H.C.. Lake evolution in the Tengger Desert, northwestern China, during the last 40,000 years. *Quaternary Research*, 1995, 44: 171-180.
- [93] Herzschuh, U., Tarasov, P., Wunnemann, B., Hartmann, K.. Holocene vegetation and climate of the Alashan Plateau, NW China, reconstructed from pollen data. *Palaeogeography Palaeoclimatology Palaeoecology*, 2004, 211: 1-17.