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Climate-Driven Landformof the Ejina Basin (NW China) in Central Asia and Its Paleoenvironmental Implications

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Abstract

Though neotectonic activity is believed to be the major factor in the evolution of the topography of the Ejina Basin in Central Asia, detailed documentation and analysis of climatic landscape features and their environmental implications are lacking. The present study is a site-specific documentation of landforms developed in the wide part of the Ejina Basin, with the aim to identify the climatic landforms based on the method of climatic geomorphology and to evaluate its landscape evolution and response to palaeoclimate changes. The morphodynamics of older landscapes are recognized by making comparison with the present climate and its corresponding landscapes. Clear evidences testifying the basin-scale shifting and transformation of different morphoclimatic zones in the basin are observed, which prove that the main geomorphic unit is changed from an alluvial-lacustrine plain to a desert plain. The coexistence of diverse landscapes and the consequent geomorphodiversity in the basin should be a compound result of surficial processes other than glaciations. The climate and hydrological conditions of the basin during the last glaciation and during the Early Holocene were much better than at present, possibly having an average annual precipitation ranged between 60~350 mm on the basin during ca. 39-23 ka BP but great fluctuations during Holocene. The periods of lower aridity during the late Pleistocene in the bain could be induced by an increase of the westerlies and a weakening of the Asian winter monsoon on the arid areas of the central Asia.

Keywords: desert basin, landscape patterns, geomorphodiversity, late quaternary climate, Ejina, Central Asian

1. Introduction

Northern China in Central Asia exhibits distinct variations in climate and hydrology during late Quaternary resulting in variation in the form and size of landscapes (Yang et al., 2010, 2011a, b). Due to the absence of long and continuous sedimentary sequences in desert area, finding effective substitute in the deserts of world to understanding the Quaternary climatic history is still a difficult issue (Yang 2001; Yang et al., 2004). Knowledge of the late Quaternary climatic history of northwestern China is crucial to understanding the evolution of the East-Asian climate system (Liu et al., 1996, 2002; Liu and Ding, 1998; Sun et al., 1998; Feng et al., 1998; Yang X et al., 2004, 2011b, 2012; Ding and Chan, 2005; Herzschuh, 2006; Wunnemann et al., 2007; Stevens et al., 2008; Yang S et al., 2008; Mason et al., 2009; Lu et al., 2011; Li et al., 2014). Until now, acquired clues reflecting desert palaeoenvironmental history in north China are on a large degree derived from proof of loess and palaeosol sedimentary sequences located at the peripheric or remote areas of the deserts (e.g., Liu and Ding, 1998; Guo et al., 2002; Sun, 2002). Direct index derived from local desert areas are seldom used to evaluate the Quaternary changes of desert environment in China.

The landscape conception in the sense of climatic geomorphology seemed to be a promising method to compensate for this deficiency. As an earth science opinion, for example the Davies's theory of geomorphology, the topography of the Earth's surface is the result of the balance between endogenic and exogenic forces. Endogenic forces trigger vertical movements that generate large mountain belts and depressions, whereas exogenic forces work progressively to denude the resulting relief. This permanent interplay of forces has been performed at different scales on the Earth's surface during the whole of geological history. Climatic geomorphology are defined as the discipline that identifies climatic factors such as the intensity, frequency and duration of precipitation, frost intensity, direction and power of wind, and it explains the development of landscapes under different climatic conditions (Ahnert, 1996). For example, based on consideration of two climatic parameters (mean annual temperature and total annual precipitation), Peltier (1950) established their relationship with five key geomorphic processes (chemical weathering, frost action, pluvial erosion, mass movement and wind action) and distinguished two different morphogenetic elements (weathering processes and the transport agents of the resultant materials). In this perspective nine different morphogenetic regions were postulated (Peltier, 1950; Tricard and Cailleux, 1972). Taking climate as a main dynamic of landscape formation, Hoevermann (1985) established a corresponding relation between landforms and climate types in arid areas, as show in Table 1. Pope et al. (1995) proposed a conceptual model for understanding landscape evolution and geographical variations in weathering. From the study of micro-landform development, we can obtain valuable information for a better understanding of the long sequence of events that has resulted in present-day landforms (Gutierrez, 2005). So the landscape conception in the sense of climatic geomorphology seemed effective to bridge the gap that finding effective substitute in the deserts of world to understanding the past environmental change.

Table 1. A concise state of major landscapes occurred in arid zones and their related climatic characteristics (Hoevermann, 1985)

Landscape division	Geomorphic feature	Climatic characteristics
Glacial action zone	Glacier, glacial erosion and glacial deposition morphology	Mean annual temperature of -1~-13°C (varied with arid index)
Valley landscape a) Forest area b) Steppe zone	Weak geomorphodynamic, soil formed, seasonal rivers, headward erosion, humus layers development, ephemeral rivers, mild water erosion, loess-like deposition, calcareous soil	Annual mean temperature of 1~-5°C the coldest month mean temperature of <-2°C
Pediment	Conical-shape deplanation and accumulation patterns, radial rill networks	Semi-arid (precipitation 150~350 mm/a), strongly freeze-thaw weathering
Desert Gorges	Water-eroded patterns with steep wall-sides	Arid (precipitation 60-150 mm/a)
Desert Plain	Gently inclined plains covered by sandy surface (formed jointly by wind and water)	Arid (precipitation 30-50 mm/a)
Aerodynamic topography	Dunes, wind-eroded deflation depressions and Yardangs (aeolian patterns)	Arid (precipitation <30 mm/a)

The concept "geomorphodiversity" borrows from the analogue and well known biodiversity, and especially, also the less well known geodiverisity (Gordon et al., 2012). Based on the two sciences, recently a new paradigm for climate science, cliamatediversity, is proposed (Beggs, 2013). Due to the quick progress of the earth system science, the geological and climatological communities are now actively emphasising on an integrated science of biodiversity, geodiverisity and climatediveristy (Beggs, 2013), in which the geomorphodiveristy is taken as an important component. As defined by Panizza (2009) and Testa et al. (2013), geomorphodiversity is a critical evaluation of the geomorphological characteristics and dynamics of a territory. Whatever at the macroscale or global scale, the implication of both observed past and projected future climate and environmental change for geomorphodiversity is a research question in need of great attention. This work is the first time attempt dedicated to the geomorphodiversity study on the desert basin landscape of northern China.

Ejina Basin lies on the west part of the Alashan Highland and at the central part of the desert belt in north China (Figure 1a). The geographical location of the basin is in one side on the northern fringe of the Asian summer monsoon and in the other side on the geographical latitude of westerlies (Figure 1b). So the Ejina Basin is a potentially significant place for the research on global climate change and for the studies about regional responses to global climate change. On the other hand, the Alashan Plateau had been an old stable region but became active since Mesozoic era (Guo et al., 2000). The environmental evolution of this area was affected by each tectonic phase caused by reciprocal compression between Eurasian plate, Indian plate and pacific plate, so geomorphological and paleoevnrionmental research in this area also provide evidence for studying environmental impact of the upwelling of the Qinhai-Tibet Plateau and formation of East Asian monsoon (Guo et al., 2000). The current climate in the Alashan Plateau including the Ejina Basin is hyper-arid and the current hydrological setting are single, with only one river (the Ruoshui River) flowing into the Ejina Basin (Zhu et al., 2014). Outside the Ejina, no fluvial processes occur in the Alashan Plateau (Zhu & Yu, 2014). It means that the climate and hydrology at present in Ejina is relatively monotone and stable. While, field investigations show that the regional forms of existing landscape in the Ejina is diverse (Zhu et al., 2015), evidently a result of multiple geomorphlogical processes about periglacial, fluvial and alluvial action, aggradation and deggradational processes. Besides, there have lots of active dunes occur along the Ruoshui river channel in the basin (Zhu et al., 2014). The dunes are surprisingly much lower than those in the neighboring area (the Badanjilin Desert) in the Alashan Highland (Zhu et al., 2014). As widely accepted, dune formation depends mainly on arid climate (e.g., wind intensities) and the availability of sand (Yang et al., 2011a). Therefore the dunes and the landscapes in and around the Ejina Basin are worthy of special examinations. Until now, however, documents in literatures concerning about the landscape and palaeoenvironmental evolutions of the Ejina Basin are still little. On the basis of examining landscapes distribution and formation, this paper intends to provide an insight into the geomorphological evolution and related late Quaternary variation of the climate in the Ejina Basin.

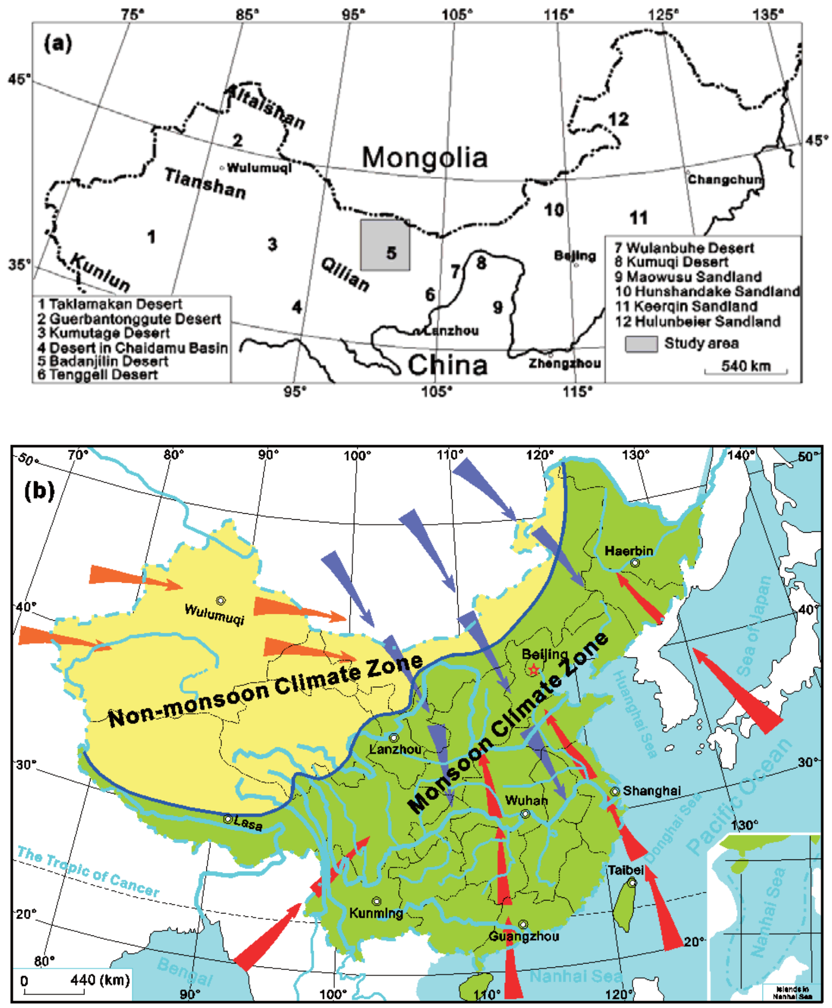

Figure 1. Distribution of the deserts in China and the location of the study area (a) and the distribution of monsoon climate zone and non-monsoon climate zone (westerly zone + cold-arid regions in the Tibetan Plateau) in China (b) (Cited from Zhu et al., 2015)

2. Regional Setting and Methods

The Ejina Basin under study is located in the west of the Alashan Plateau, between 40-43°N and 99-102° E of the middle-latitude zone of Northern Hemisphere (Figure 2). The Alashan Plateau lies in the western Inner Mongolic, NW China, and consists mainly of the gravelly plains of the Alashan Gobi together with the big sandy areas of the Badanjilin and the Tenggeli Sand Seas (Figure 2a). The Qilian Mountains, Tibetan Plateau and the highlands of the Beishan, Mazongshan, Gobi Altai and Helanshan form the natural boundaries of the Alashan Plateau to the south, west, north and east (Figure 2a). It has an area of 300,000 km^2 in altitude between 900 and 1300 m a.s.l. (average 1,000 m asl), and a relief that depresses gradually from east to west and from south to north. Gobi, sandy desert and relict mountain are the major landforms (Figure 3). Located in the inland of northwestern China and adjacent to Mongolia High-pressure center, Alashan Plateau is one of the driest areas of the world, characterized by extreme continental temperate climate conditions with hot summers and cold winters. Precipitation derived mainly from westerlies and the Asian summer monsoon shows a strong interannual variability. Drainage system is poorly developed in this plateau, except the west part where the Ruoshui River is a big seasonal inland river with running water from July to October every year.

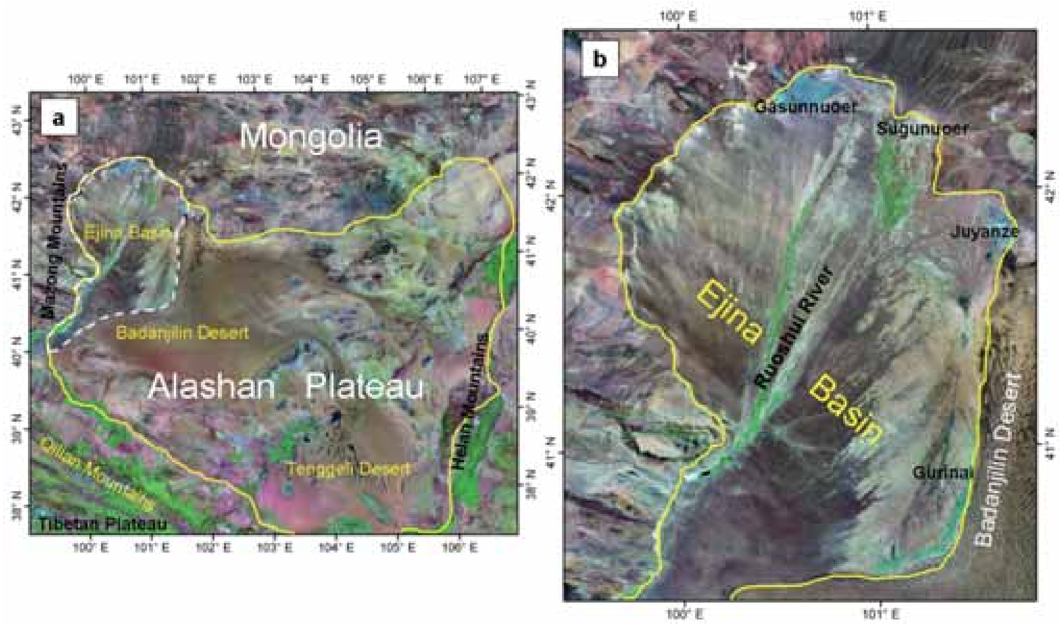

Figure 2. Overview remote-sensing images (Landsat TM, RGB 7-4-2) of the Alashan Plateau (a) and the Ejina Basin (b) (Cited from Zhu et al., 2015)

The Ejina basin is north-south trending in topography and is a regional tectonic depression limited to the east by the Badanjilin desert units and to the east by Mazongshan Mountain Units (Figure 2). Surface drainage in the Ejina is constituted by the Ruoshui (Ejina) River and its ephemeral tributaries, among which the most important are the East River and West River both coming from the Heihe River, one of the three largest inland river systems in China. The elevation of the East river course declines from Langxinshan to Lake Sugunuoer about 160 m (Figure 4a). The climate in the basin is arid under desert conditions. The harshness of the present climate is manifested by wide annual temperature variations (77°C), atmospheric transparency, low humidity, winter snow precipitation and very scarce pluvial precipitation (Figure 4b-d). The mean annual temperature is 8.8 °C at Ejina during the last five decades (Figure 4d), with a maximum daily temperature of 41 °C (July) and a minimum of -36.4 °C (January). The rainfall regime is continental, with summer rains (Figure 4b) and only with very low average frequency of days with rain. The average annual precipitation in the last five decals recorded in the weather stations of Ejina is 35.6 mm (Figure 4c). From a climatic viewpoint, this area can be classified as hyper-arid (120 > p> 60 mm) or eremitic (60 >p > 30 mm), depending on the subzone (Perucca and Martos, 2012). Prevailing winds come from the west (Figure 3), and the northwest winds are almost constant occurrences during August-September.

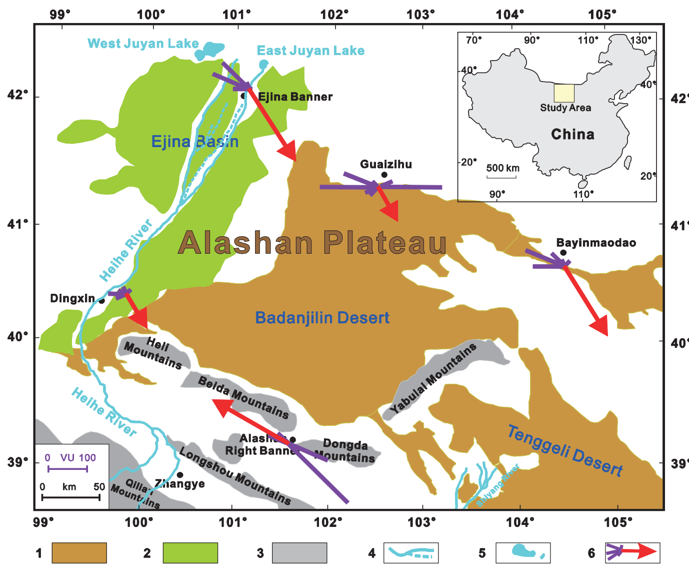

Figure 3. Landscapes of the Alashan Plateau. Legend: 1 sand seas, 2 Alluvial and fluvial sediments associated with the Heihe (Ruoshui) River, 3 Adjacent mountain ranges, 4 Rivers, 5 Lakes, and 6 sand roses (Fryberger and Dean, 1979) for each of the five surrounding weather stations, with aubergine lines showing winds capable of transporting sand from various directions (DP) and red lines with arrows indicating the resultant sand transport trend (RDP) (Modified from Yang et al., 2011a)

Characterization of local and regional landscapes in the Ejina desert basin is described mainly relying on the LANDSAT ETM+ data, topographic maps and field examinations. The identification and classification of landscapes is to a considerable extent based on the system of climatic geomorphology, as show in Table 1. The field investigation in the Ejina area concentrated on the upper, middle and lower reaches of the Ejina River that flows from the Langxinshan northwards into the Lake Sugunuoer (East Juyanhai). Detailed fieldwork was carried out in the whole drainage region. Chinese 1:100,000-scale topographic maps, 1: 500,000-scale Google-Earth images and GPS were used for the orientation in the field.

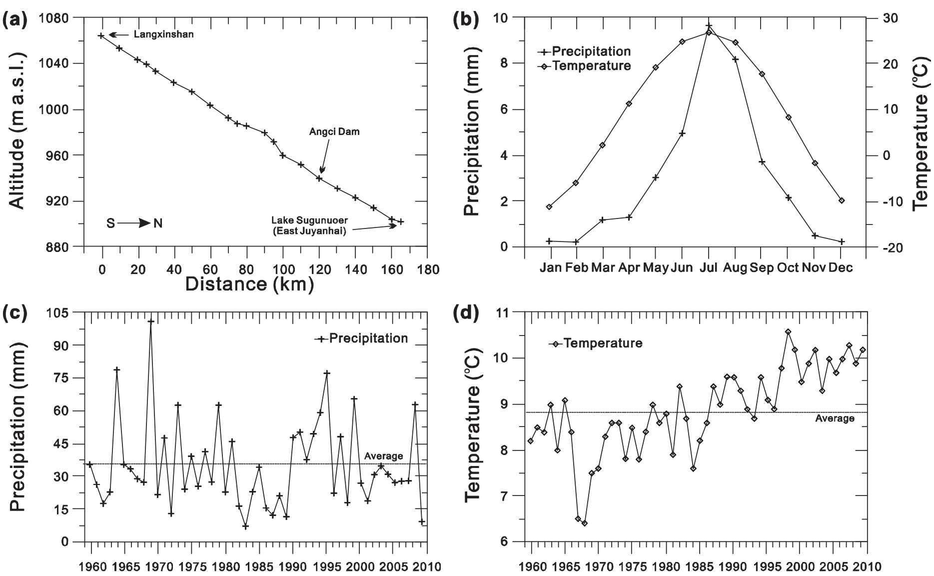

Figure 4. A topographic profile of the S-N trending line (along the East river from Langxinshan to Lake Sugunuoer), the seasonal distribution of average precipitation and temperature (50 years during 1960-2009) (b), variations of the average annual precipitations (c) and temperatures (d) (50 years during 1960-2009) in the Ejina Basin

3. Results and Discussion

3.1 Identification of Dominant Landforms in the Ejina Basin

The geomorphological conditions of the Ejina Basin are complexity. It is a privileged place to observe the relationship between mountain, peneplain and basin playas which are directly connected to the genesis of the Ejina landscapes (Zhu and Yu, 2014; Zhu et al., 2014, 2015). The Ejina geomorphological complexity is firstly determined by lithology and tectonics factors, which are obvious morphotectodynamic processes indicated by significant gradients between mountain peaks (Mazong Mountains) and basin floors (Juyan Lake) in the Ejina (Zhu et al., 2015). Besides tectodynamics, satellite imagery and field observations also show that the most widely spread landscapes in the arid regions of China are desert plains and aerodynamic landforms (Hoevermann 1985; Yang 2001; Yang et al. 2004, 2011a, b), of which the Ejina Basin is the most representative (Zhu et al., 2015). Detailed identification and explanation about the types of the dominant landforms in the Ejina Basin are listed below.

3.1.1 Desert Plains

Tectonic activity often intensifies surface erosion to produce a large amount of debris, which are transported by rivers and/or glaciers and deposited on mountain piedmont and basin depression, forming vast flat alluvial fans. Under dry conditions, strong winds blow away the silt and sand fractions of sediments, and leave a gravel cover on the alluvial fan surface, thus forming the desert plain. Quite a large part of areas in the Ejina Basin is typical for desert plain (Figure 5). The geomorphological process of desert plain formation can be divided into erosion and accumulation. The accumulation plain dominates in the central part of the Eijina basin and in areas close to the aerodynamic relief. In the transitional zone to the surrounding highlands, erosion plains prevails (Figure 5a). In the Ejina Basin there are depositional desert plains that are called “Gobi” in Chinese terminology. The sedimentary strata of the desert plains are mainly proluvial-alluvial deposits (Figure 6a), complicated sequences with sand, gravel, silt and clay sediments involved alluvial, fluvial, lacustrine and aeolian processes (Figure 6b), thick clayey deposits by lacustrine processes (Figure 6c). Slightly eroded shallow sections by fluvial processes are often observed in desert plains (Figure 6d) and huge lacustrine profiles occur in the lower northern part of the desert plain (Figure 6e). The upper sediments of Gobi desert are sand, silt and gravel in compositions and the gravel lie mostly in a relatively thin layer above the surface, shown as desert pavements (Figure 5b, d). Desert pavement can originate via a single or various processes, which indicates a problem of convergence of forms (McFadden et al., 1987). Fundamentally the processes can be extrinsic in character, produced by water and aeolian action, and intrinsic, in which the interior of the soil is modified by differentiation processes. The most universally applied process of pavement genesis is deflation, whereby fine particles are exported by the wind, leaving a residue of coarse material that goes on to constitute the pavement.

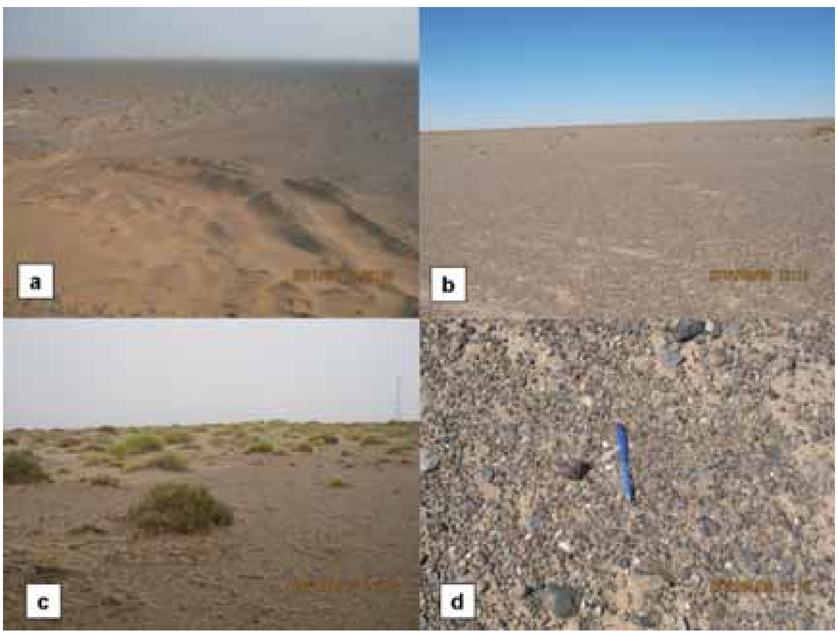

Figure 5. Landscape of desert plains and typical reg of clasts developed on the alluvial plain in the Ejina Basin

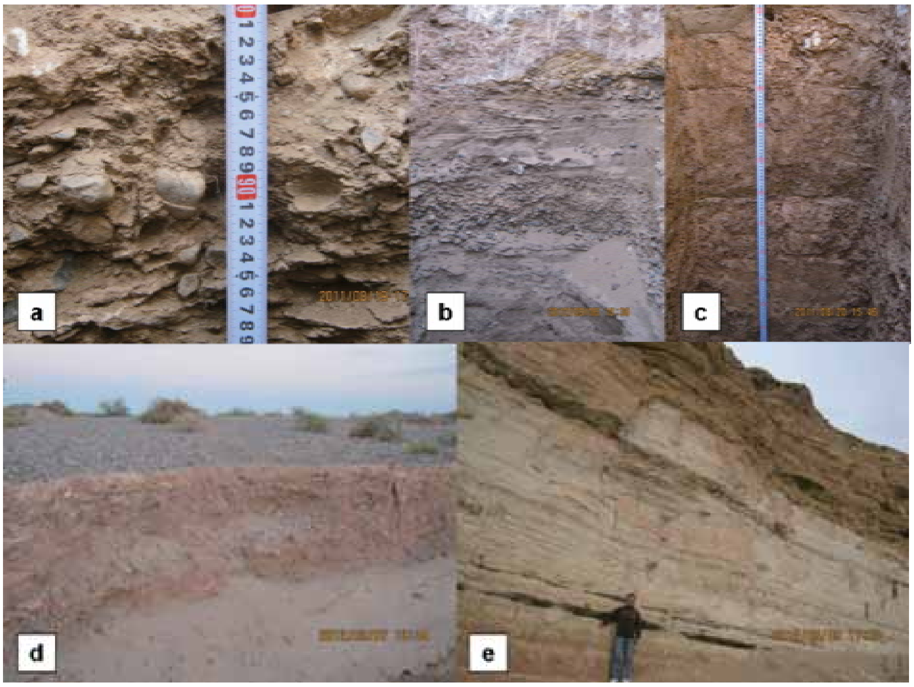

Figure 6. Sedimentary Profiles in the Ejina Basin: (a) proluvial-alluvial deposits (in desert plain), (b) complicated sedimentary sequence including sand, gravel, silt and clay sediments involved alluvial, fluvial, lacustrine and aeolian processes (in desert plain), (c) thick clayey deposits, (d) erosional terrace of river bank (margin of the basin), (e) palaeo-lacustrine section (at the low terrain of the north basin)

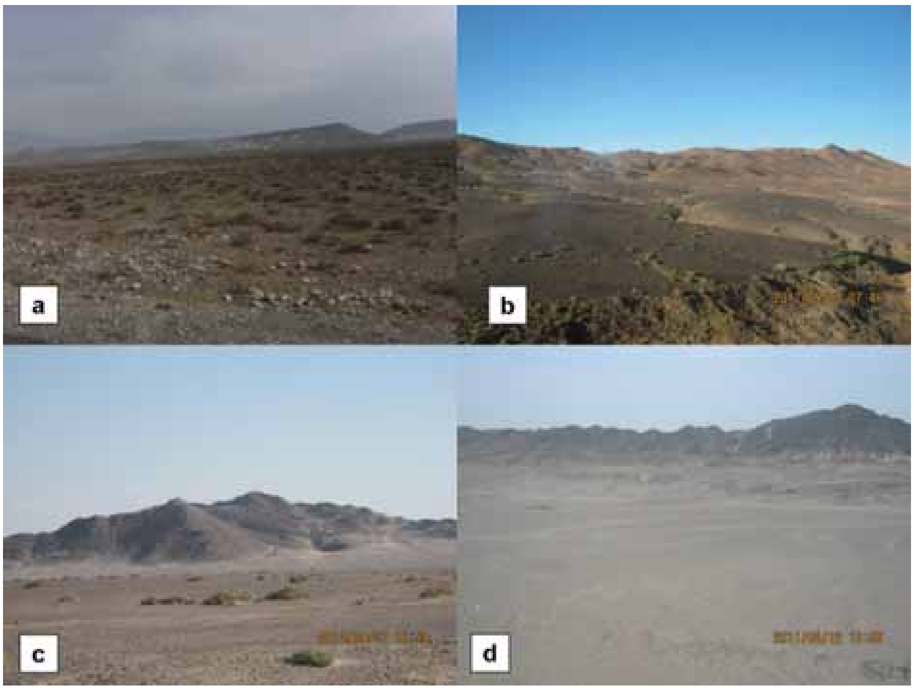

Figure 7. Landscape of pediment in the Ejina Basin

Figure 8. Landscape of desert gorges in the Ejina Basin

3.1.2 Pediment

In the system of climatic geomorphology, the pediment represents a conical relief characterized by a channel net. Frost weathering producing loose rock materials during the winter is crucial to the formation. Water from rainfall in the summer brings these materials to the streams and alluvial fans are consequently developed. Like desert plains, pediments can be distinguished into erosive and depositional sub-forms. Around the western and northern edges of the Ejian Basin, pediments appear on the foot zone of mountains and in the higher sections of desert plains (Figure 7).

3.1.3Desert Gorges

The desert gorges are widely distributed in the surrounding mountain slopes like the Mazongshan Mountains in the western of the Ejina Basin (Figure 8). The desert gorge storey is present in the upper part of pediments and the desert plains and the gorges usually dissect the mountain fronts. The landscape of gorges was produced by water and there is evidence of former severe erosion (Figure 8a-c). In some places, loose sand layer begin to cover the gorge surface by aeolian and desiccation-deflation processes, owing to lack of water (Figure 8d).

Figure 9. Aeolian landform (dune fields) in the Ejina Basin. (a) Single dunes and dune chanins, (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

3.1.4 Aeolian Landform

The aerodynamic landform refers to the actual wind-sculpted relief including dune fields of various forms and wind-eroded rocks like yardangs and deflation depressions. In Chinese terminology, desert is always related with dune fields (Yang et al., 2004). The dune landscapes in the Ejina Basin are mainly located at areas along the two bank sides of the Ejina River (Figure 9) and surrounded by Gobi and desert plain (Figure 10). Based on vegetation conditions the dunes can be divided into three main types: active, semi-active and fixed dune (Figure 10). On the dune land surface *Populus euphratica, Chionese tamarisk, Artemisia*, *Agriophyllum arenarium* and other plants are scarcely distributed (Figure 9c-d). The height of 23 dunes examined by us in field ranges from 40 to 1.5m, with an average 11 m (Zhu et al., 2014). These figures confirm that the height of dunes changes regularly on a local scale but the dune types do not differ greatly from place to place (Zhu et al., 2014). The three types of dunes occur at any locations. Compared with the neighboring dune filed in the Badanjilin Desert, where the height of most dunes ranges from 333 to 185m, the dunes in the Ejina are much lower and relatively younger at their early stage of dune development (Zhu and Yu, 2014). Differing from the dune shapes in the Badanjilin Desert, where complex megadunes predominate and secondary dunes of various forms are overlapped on the windward slope of these megadunes, the dunes in the Ejina are almost single in figuration and are mainly dune chains, transverse and net dunes (Figure 9a-b). The ridges of these dunes are not straight and both lee and windward slopes are gentle (Figure 9a-b), with slope angles less than 5°. In this sense, three types of aeolian accumulation can be classified: sand ripples, Draas and dunes (Busche, 1998). On the slope of most of the dunes in Ejina there are no any calcareous layers, clearly different from the dunes in Badanjilin, indicating that most of the dunes in Ejina Basin are under early stages of dune development and no former configuration of the dunes. Compared with our field investigations in other deserts before, pyramid or star dunes occur widely in the Taklamakan and the Badanjilin deserts, the largest and the third largest sandy desert in China, respectively (Zhu and Yu, 2014). Observations in the Taklamakan show that some pyramid dunes have been created by erosive processes and in the Badanjilin the multi-directional winds presumably played an important role (Yang et al., 2004). While in the Ejina Basin, this kind of dunes is rarely observed. A seasonal change of directions of prevailing winds is occurred in the records of Ejina weather stations (Figure 3) but no balanced wind systems in different directions and the wind energy is weaker than that in the neighboring Badanjilin. This is maybe an important major reason that no clear pyramid-type of dunes develops in the Ejina.

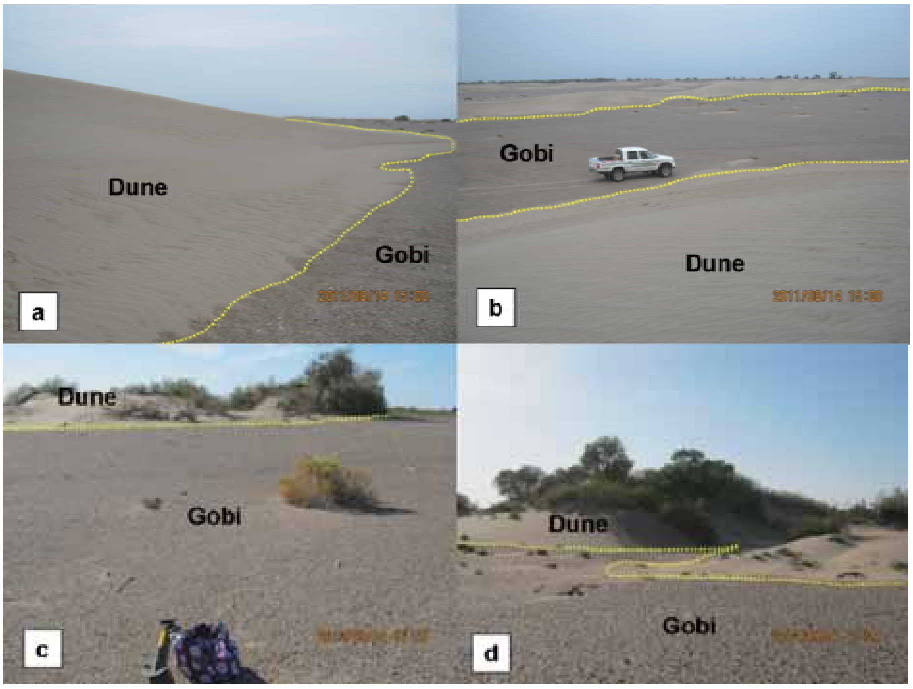

Figure 10. Active dunes developed on the Gobi deserts

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

3.1.5 Fluvial Landforms

The fluvial landform is only existed in the Ejina Basin on the Alashan Plateau (Zhu et al., 2015). Ruoshui (or Ejina) River, as the low reaches of the Heihe River, is the unique river flowing through the Ejina Basin. The river emerges from the south corner (Langxinshan) of the Ejina Basin and follows a S-N directional course of ca. 160 km before flowing into the Lake East Juyanhai (Figure 4a) at the northmost part of the basin. Due to the flat and wide terrain (Figure 12a-b) the relief of Ruoshui watershed is generally much smaller than that of watersheds in other parts of the Heihe River. The fluvial landforms are characterized by low-gradient courses and small slopes (Figure 12b), with a modal angle (0.06°) less than 0.1°. The stem river channel of the East River is about half to 1 km in width (Figure 12a-b) and the river beds are characterized by sandy sediments (Figure 12b-c). Water supply of the Ruoshui River is markedly intermittent flood discharges with muddy water (Figure 12d), which was derived from the upland water in the Qilian Mountains areas during the spring and rainy seasons. The duration of floods is short recently because of water conservancy programs for the Heihe System at the middle reaches. While sediment yields in Ejina is highly significant, especially in the Quaternary history. Except for exists of the modern river channels, lots of the palaeo-river channels still can be identified both from the morphology in the field and from historical maps and satellite images (Figure 2a).

3.1.6 Modern and Ancient Lakebeds

In the low terrains and distal areas of the alluvial fans in the Ejian Basin (mainly the north part), modern and ancient lakebeds are widely distributed (Figure 13). There are also extensive areas with lacustrine and paludal sediments distributed at the east, central and northern peripheries of the Ejina Basin. The Gurinai Lake basin extends 120 km from south to north and about 50 km from east to west. The Garshunnuoer (Figure 13b) and Sugunuoer lake (Figure 13c) areas are about 100 km long in the east-west direction and up to 40 km wide from south to north. The maximum dimension of the Guaizihu Lake and Juyanze basins is about 60×60 km. These ancient lake basins have now thoroughly dried up in the natural environment, and the area of recent day playas, which are assumed to show evidence of higher lake levels in the past or even the existence of a palaeolake (Wunnemann et al., 2007; Hartmann and Wunnemann, 2009), cover an area of about 15,000 km^2. Viewing from remote-sensing images, these lakes were apparently the terminal lakes of the Roushui River (Figure 13). Fluvial sediments alternate with the lacustrine deposits in many profiles (Figure 6b). In some areas of the former lakebeds there are still whiter-color clayey sediment strata (Figure 6e). Along the Ejina River (with two tributaries, East River and West River) course in the central of the Eijian Basin there are thick layers of lake sediments that were deposited in previously strong hydrological conditions (Figure 6c).

Figure 12. Fluvial landscapes 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

3.2 Geomorphodiversity of the Ejina Basin

3.2.1 Geomorphological Differentiation in a Desert Environment

Geomorphologists (e.g.Meigs, 1953) have defined deserts as a cold deserts when the prevailing mean temperature of the coolest month is less than 0 °C. Accordingly, the Ejina Basin is under a cold desert environment because ground surface temperatures in the area have been registered to vary between 25 °C and –15 °C. The most significant characteristic of this environment is the great thermal annual oscillation that occurs. Due to its latitudinal position and to the anticyclonal domain, the Ejina Basin is characterized by great insolation and the air temperature can reach considerable values in summer, as much as 40 °C. The warm winds in the desert regions cause the desiccation of many areas. However, the geomorphic criteria that can be used to establish classifications of arid zones can vary a great deal. The application of rules about dominant processes and general morphological types in desert environments allows us to establish geomorphological differentiations.

Two important dominions can be recognized in deserts as a function of the main acting processes (Cook et al., 1993). One is the aeolian dominion and another is the fluvial dominion (Cook et al., 1993). Both dominions can be superimposed in the study area, because the activity of the aeolian and fluvial processes coexists in wide spatiotemporal scale in the Ejina Basin, as two examples can be seen from the basin sedimentary record with interbedded aeolian and fluvial sequences (Figure 6b) and the distribution of dunes along the river banks (Figure 9). On the other hand, it indicates that the climatic changes that have must taken place during the Quaternary have produced important modifications in the aridity of the basin. As a consequence, the activity and intensity of aeolian and fluvial processes seems to be modified considerably.

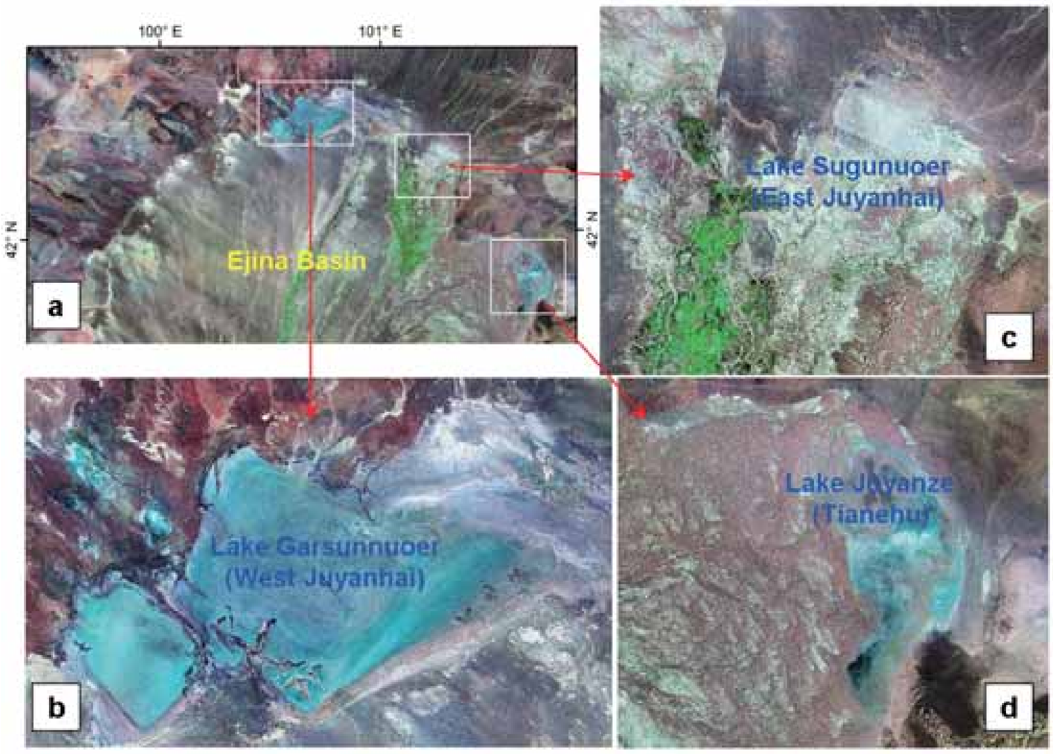

Figure 13. Overview remote-sensing images (Landsat TM, RGB 7-4-2) of the north basin (a), the Lake Garsunnuoer (b), the Lake Sugunuoer (b) and the Lake Juyanze (d) in the Ejina Basin

The application of the geomorphic criterion in desert, based on the type of dominant morphologies and in the geologic structure, along with the degree of tectonic stability, permits distinguishing between shield/platform deserts and mountain/basin deserts (Mabbutt, 1977). Shield/platform deserts are formed fundamentally from cratonic areas preformed basically by Precambrian rocks and platforms of later age. Their main characteristic is the flat relief, interrupted by recent volcanic massifs and by important fractures. The mountain/basin deserts are constituted by long mountainous alignments separated by depressed areas. Evidently, the Ejina desert belongs to mountain/basin desert. Its marginal relief in a number of highland places was shaped during the alpine orogeny in the Mesozoic and Cenozoic ages. As a consequence of the topographical contrast the high areas have suffered a constant denudation and the resultant materials have lodged in the depressions, in the form of coalescent alluvial fans (Figure 2). In the distal areas of the alluvial fans the run-off waters are collected in closed depressions that form ephemeral lakes (Figures 2, 13) in which takes place an evaporitic sedimentation (playa-lake).

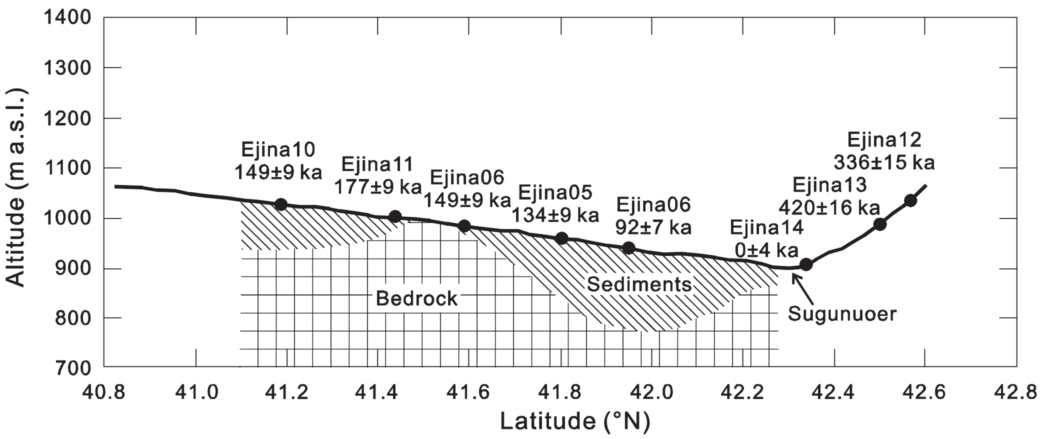

Figure 14. Variations in altitude, sediment thichness (Zhang et al., 2006), and exposure ages of the quartz gravels (Lv et al., 2010) from the Gobi deserts along a SW-NE transaction in the Ejina Basin

3.2.2 Geomorphological Inconsistency of Landforms in the Ejina Basin

Formations of desert gorge and pediment are both related with frost weathering processes under cold and wet climate (Hoevermann, 1985). Comparing the landscape type with the present dominant morphodynamic process and climate,e.g., desiccation-denudation processes and temperate-zone climate, implies that there is an inconsistency in the extensions of pediments and desert plains in the areas of the Ejina Basin.

The climatic precondition for the formation of a pediment is a cold winter and an average annual precipitation of 150-300 mm (Hoevermann, 1985). Frost weathering processes in winter and alluvial processes in summer is crucial to the formation of pediment. However, the average annual precipitation and temperature at present is only ca 35 mm and 8.8°C in the Ejina Basin, respectively (Figure 4b). The desiccation-denudation processes are predominated in a full year and the alluvial processes have decreased considerably under present climatic conditions. So an actual formation of pediment does not take place in the Ejina Basin under present climatic environment. Strong erosion processes by water are needed for the formation of desert gorge landscape. The critical amount of annual precipitation for developing desert gorges is thought to be 60-150 mm (Hovermann, 1985). At present these gorges areas are often bare and present frost weathering processes are quite weak in the Ejina Basin. Similar to the pediments and alluvial fans, desert gorge formation in the Ejina basin is now inactive owing to the lack of water. According to Hovermann (1985), whatever desert gorge and pediment landscapes, their formations both reflect much more annual mean precipitation and lower temperature than present (Table 1). Thus the pediments and desert gorges surrounding the Ejina Basin are relict landforms associated with more humid and colder climate in the past.

On the other hand, small shifting dunes are distributed widely along the Ruoshui river banks (Figure 9). According to Hovermann (1985), typical aerodynamic relief often occurs in the area with an average annual precipitation of less than 30 mm and the dry climate promotes the development of shifting dunes, which become stabilized under moister conditions. To some extent, river channel and the nearby areas are somewhat wetter conditions, so the occurrence of shifting dunes along the river sides (but not far way from there) should be an abnormality. Sand source/supply and the role of retention effect by vegetations (such as *Populus euphratica*), as well as unenen ground (due to shrub vegetation) and weak deflation processes nearby river may be significant factors for the formations of these dunes other than arid climate.

3.2.3 Geomorphological Transformation of Landforms in the Ejina Basin

Filed Investigations and sedimentary and mapping analysis suggest that the landscapes and the boundary of different landscape types in the Ejina Basin have undergone changes or transformation. At present the former pediments around the Ejina Basin are undergoing transformation towards desert plains in the lower terrains and towards desert gorges in the higher locations. In many locations the slopes with desert gorges are being buried under aeolian sand (Figure 8d). The gorges landscape is thus being transformed to an aerodynamic landforms assemblage.

In the marginal areas of dune fields, thin layer of gravel with a maximal diameter of 3-5 mm covers ground surface (Figures5d and 10). This occurrence of gravel layer is indicative of former more powerful winds effecting on the berried alluvial/pluvial sediments. The dunes generally possess small geometric parameters and sit on the surface of earlier desert plain landscapes, meaning that the present-day active shifting dunes are younger and distributed on an old relief surfaces. In genral, the development of shifting dunes is caused by climate conditions with intensive wind and shortage of precipitation. Its formation represents a transportation and collection of unstable/loose sandy materials and is related with an increased aridity index (Hoevermann, 1985). According to the conceptions of climatic geomorphology, the morphodynamic process and sand transportation for dune accumulation takes place in case the wind becomes stronger and the availability of water decreases. Such kind of shifting does not cause a change of landscape, but it is an evidence for regional climatic aridification and land desertification.

Desert plain, as a main geomorphological unit in the central Ejina Basin, was transformed from alluvial fan by alluvial depositions of the Ruoshui River. This can be proved by a wide exist of basin sedimentary stratigraphy with thick alluvial sedimentary strata buried under Gobi surface (Figure 6). The alluvial fan in Ejina had extended northward about 160 km and changed from alluvial plain to alluvial/lacustrine plain, and then to lacustrine plain. In terms of climatic geomorphology, desert plain refers to a relief that undergoes a morphodynamic process with balanced wind and water dynamics (Hoevermann, 1985). The relief energy on the desert plains is relatively low and the ideal amount of average annual precipitation for forming desert plains is 30-60 mm (Table 1). Viewing from this opinion, the current climate in Ejina is suitable for the formation of desert plain. However, the present-day desert plain in Ejina is still in the beginning stage of desert plain formation, because the shape of large-scale alluvial fan is still recognizable from the remote-sensing images (Figure 2) and there are also lots of relicts of riverbeds and fluvial terraces. Owing to the presence of groundwater and river used for irrigation, oases are developed in this zone. Along the riverbanks of the Ruoshui River the original desert plain has been replaced by an agricultural landscape, indicating a strong influence of human activities on regional landscape evolution. On the peripheral edge of the Ejina Basin, field investigations confirm that former alluvial landforms like channels are still well preserved (Figure 5a). During years of richer precipitation, the vegetation of the desert steppe is well developed (Figure 5c). The plant communities consist mainly of shrubs and half-shrubs. Therefore the landscape here can be seen as a transitional form between the desert plain and the pediment.

The Geomorphological transformation in the basin can be seen as a general increasing tendency of the climatic aridity. Several ca 3-4 m deep profiles located in the central part of the Ejina Basin consists of the following materials from bottom to top: a) interbedding of fine aeolian sand and coarse fluvial deposits; b) lake sediments; c) interbedding of aeolian sands and marsh deposits and d) interbedding of aeolian sands and sandy silts (Figure 6). This sequence leads to the interpretation that the landscape during the earliest period was a desert plain because of the occurrence of aeolian and fluvial deposits on the lowest part. Thereafter the climate became less arid and lakes appeared. Later a process of aridification started and an aeolian process finally replaced the marsh sedimentation. Owing to the insufficiency of dating data, identifying a reliable time scale from the profiles still remains a challenging task. But the glacial and periglacial sequences in the foot zone of the marginal highlands in the Alashan Highland provide a comparable chronology. Roughly, the pediments dovetail the glacial-fluvial fans of the last glacial maximum (Hoevermann et al., 1998). This is a hint that the active formation of pediment took place during the last glacial period.

In general, if the old pediments and desert gorges in the region of present-day formation of the desert plains demonstrates higher precipitation in the past and a remnant landscape, then the aerodynamic relief indicating that the landscape patterns of desert plain and aeolian dunes are suitable to contemporary landforms corresponding to the present arid climate.

3.3 Palaeo-Climate Change Deduced from Landscape Evolutions

The shift of a boundary between different landscapes and the transformation of landscape types are credible evidences of climate change, and the changing extents of different climatic controlled geomorphic landscapes help to provide estimates of the magnitude of climatic change (Hovermann, 1985; Gutierrez, 2005). Based on the modern climatic implication of the different landscape regions it is also possible to estimate past precipitation and temperature (Lehmkuhl and Haselein, 2000). For example, Hovermann et al. (1998) calculated the annual precipitation values of Qaidam region since 32 ka by comparing the annual sedimentation rate of clastic sediments in core CK 2022 from the central Qaidam Basin. Goudie (1983) points out that the peak of dust storm frequency occurs in areas where rainfall ranges between 100 and 200 mm/a. This is in accordance with many regional observations made in Tibet, Mongolia, and Africa (Hovermann, 1985, 1987; Hovermann et al., 1993; Lehmkuhl, 1997).

3.3.1 Aridity in the Basin

The transformations of old pediments and desert gorges to desert plains, the occurrence of wide shifting dunes and the existing large palaeo-lakebed areas all indicate the increasing aridity index in the Ejina Basin at present. In general, regional aridity is controlled by a conjunction of climatic, orographic and oceanographic factors. The zonal factor, continentality and the orographic effect are possible the main controls (Gutierrez, 2005).

According to the rule of climatology, the zonal factor occurs in relation to the trajectory of anticyclonic cells that control the tropical and subtropical deserts. Occasionally these deserts can be penetrated by storm systems, although precipitation is scarce. Zones of great aridity, surrounded by small semi-arid stripes, characterize them. The most representative example is the Sahara desert. While the Ejina Basin is geographically located in the middle-latitude temperate zone of North Hemisphere, the zonal factor should not be the reason for its aridity. Continentality refers to the distance from ocean of the land. In temperate latitudes, the rain-producing fronts gradually lose their humidity along their way towards the interior of the continents. In these regions cold winters are common and the arid zones are bordered by semi-arid areas of great extension. The middle-latitude deserts of northern China and Central Asia have these characteristics. So it is an important factor controlling the aridity of the Ejina. The orographic effect occurs because of the presence of rain-shadow zones situated on the leeward side of mountainous chains, in regions with dominant winds, as in the Trade Winds belts or on some west coasts. When air masses descend the slopes of a chain of mountains they heat up and dry adiabatically. This orographic effect can be emphasized by the zonal situation and the continentality. Ejina Basin lies in the north edge of the NH Trade Winds belts. The Qilian mountain chains and the Tibetan Plateau on the southern part, together with the Alshan Highland and the Inner Mongolia Plateau on the eastern part of the Ejina Basin, act as such a giant rainfall barrier preventing the enter of vapor source from the Southeastern Asian Summer Monsoon and the Southwestern Asian Summer Monsoon.

We should also consider the albedo effect or reflectivity of the desert surfaces in the Ejina Basin because in some warm deserts of the world, the heating generates convection currents. In rocky and stone deserts (Gobi in the Ejina) the absorption of the warmth is maximum, it enhances the degree of evapotranspiration effect and induced the strength of aridity, especially if a cover of desert vanishes exists on it.

The most significant characteristic of cold desert environment is the great thermal annual oscillation that occurs. Besides, precipitation in the Ejina Basin is influenced by the topography and in the marginal highlands is frequently snowfall. Evaporation is low during the cold months and is commonly associated with strong winds. Due to its latitudinal position and to the anticyclonal domain, the Ejina deserts suffer a great insolation and the air temperatures can reach considerable values, as much as 40 °C. The warm winds in the desert regions produce the desiccation of many areas. These winds blow during the day and at night stay calm. They blow up from the desert to the more humid marginal zones and are commonly dust-laden.

3.3.2 Evidences from Pediments and Desert Gorges

Landscapes like pediment and desert gorge surrounding the Ejina Basin are also widely distributed around the eastern, southern and northern parts of the Alashan Plateau and in the desert areas of western China (Figures2-3). Relative to desert plain, these kinds of relict landforms in current hyper-arid and temperate climate context of western China are associated with more humid and colder climate in the past (Hovermann, 1985). According to studies of the sedimentary chronology in the central Alashan (Hoevermann et al., 1998; Yang, 2001), a humid and clod climate on the Alashan Plateau during the local glacial maximum of the last glaciation is consistent with the old formation of the pediments and desert gorges on the margin of this plateau. The thick gravel deposits of Quaternary Gobi deserts along the northern margins of the Tibet Plateau (Qilian Mountains) are middle and Upper Pleistocene ages (Liu et al., 1996). Field investigations have shown that there have been clear climatic fluctuations accompanied by landscape changes and paleohydrological variations in the desert areas of western China during the Late Quaternary (e.g. Chen and Bowler, 1986; Thompson et al., 1989; Fang, 1991; Li and Shi, 1992; Owen et al., 1997; Lehmkuhl and Haselein, 2000; Zhang et al., 2000; Ye and Ji, 2001; Yang et al., 2003, 2011a, b; Yang and Scuderi, 2010), and in these areas presently under formation of sand dunes and desert plains, underlying relict gorges and alluvial fans are attributed to the local glacial maximum (Yang, 2001; Yang et al., 2004). Based on the gemorphological and sediment properties of the regional comparability, especially the low degree of weathering (Zhu and Yang, 2009), it is reasonable to attribute the relic forms of desert gorges and pediments in the margin of the Ejina Basin to the local glacial maximum of the last glaciation (LGM). This opinion is also supported by the numerous data showing much wetter and colder climate during the Anaglacial (about 32-24 ka) in the Central Asia, northern China, Mongolia and on the Tibetan Plateau (Feng et al., 1998; Liu et al., 2002; Yang et al., 2004; Mischke et al., 2005; Herzschuh, 2006). For example, wide distribution of relict frost wedges and moraines in the Chaidamu and Tarim basins of China indicate that the coldest time of the last glaciation occurred at 30-25 ka in these two areas; the stratigraphy of dunes and high lake levels in the Badanjilin Desert and its vicinity regions in northern China and in Mongolia suggest a much more humid climate in western China and in Mongolia during marine oxygen isotope stage three (MIS 3) (Yang et al., 2004). Cold and wet climates were prevailed in the western part of the Chinese Loess Plateau during MIS 4 and MIS 3 (Feng et al., 1998). The northern boundary of the Gobi in Mongolia has shrunk owing to the wet climate as nine times during the past 40,000 yr, e.g. around 34,400, 30,700, 28,900, 24,500, 15,090, et al. (Feng, 2001).

Extensive pedimentation processes occurred during the last glaciation around the margins and central of the Alashan were identified (Hoevermann et al., 1998). Three different phases of pediment formation during the Pleistocene in the foreland of Qilan Mountains have also been distinguished (Hoevermann et al., 1998). For the periods of pediment development the annual precipitation in these areas should be considered to have been as high as 150-300 mm (Table 1). Presently the average annual precipitation varies from 110 mm in the southeast Alashan to 38 mm in the northwest and 36.5 in the Ejina Basin (Figure 4c) according to records obtained over the last five decades. Compared the current climate (40 mm in precipitation) with the corresponding climatic conditions of desert gorge (60-150 mm) and pediment (150-350 mm) formations, relicts of old pediments and desert gorges in the Ejina imply that the amplitude of precipitation variation in the past has reached 20 to 200 mm and this is much larger than present level. Giving the average annual precipitation was 60~350 mm on the margin of the Ejina Basin during the LGM, that would have been 50%~775% more than at present.

3.3.3 Evidences from Desert Plains (Gobi) and Alluvial Sedimentation

In arid regions Gobi deserts derived from alluvial fans are a common geomorphological feature (Goudie, 2009). The Gobi deserts (Figure 5) in the Ejina Basin are widely developed from alluvial sediments. Reconstructing the evolutionary history of Gobi desert has great significance in unraveling changes in both tectonic activity and climate (McFadden et al., 1987; Feng et al., 1998, 2001), because the formation and evolution of an alluvial fan are closely related to variations in the tectonic activity and climate. Abrupt floods and strong wind are two major dynamic factors in the formation of the Gobi Desert (Hovermann, 1985; Gutierrez, 2005). As a result, Gobi desert has experienced both hydraulic transportation and wind erosion and would record changes in tectonic, climate, and environmental conditions. Therefore, the beginning of the development of the Gobi Desert results in the end of alluvial processes.

Cosmogenic ^{10}Be in quartz gravel from the Gobi deserts of the Ejina Basin has been measured to assess the exposure ages of gravels (Zhang et al., 2006; Lv et al., 2010). The results showed that the Gobi desert in the northern margin of the Ejian basin formed 420 ka ago, whereas the Gobi desert that developed from alluvial plains in the central areas of the drainage basin came about during the last 190 ka (Figure 14), both of key periods during the late Pleistocene glaciations. The latter developed gradually northward and eastward to modern terminal lakes of the river. These temporal and spatial variations in the Gobi deserts indicated a consequence of alluvial processes influenced by Tibetan Plateau uplift and tectonic activities within the Ejina Basin. Possible episodes of Gobi desert development within the last 420 ka indicate that the advance/retreat of alpine glaciers during glacial/interglacial cycles might have been the dominant factor to influencing the alluvial intensity and water volume in the basin. Intense floods and large water volumes would mainly occur during the short deglacial periods.

For intermontane basins considerable volumes of sediments have been stored as alluvial fan deposits or basin fills. Abundant sediments supply from Qilian Mountains by Heihe River results in the widespread distribution of alluvial fans along the mountain fronts and the Ejina basin. Both alluvial fans and alluvial cones consist mostly of gravel and sand but they can also contain boulders when debris flows contribute to their formation (Figure 6a-b). Alluvial deposition is tied to land surface instabilities caused by regional climate changes (Gutierrez, 2005). Alluvial fans in central Asia can be classified into two basic types: dissected and undissected; most dissected fans are composed of Pleistocene surfaces; whereas, most undissected fans are composed of late Pleistocene and Holocene surfaces (XETCAS, 1978). The distribution of fan surfaces formed in the mid-Pleistocene or earlier is much more limited (Oguchi et al., 2001). Well-preserved old surfaces are confined to areas where fan surfaces are being tilted rapidly toward fan apexes because of the relative uplift of fan toes. Alluvial fans in the Tarim Basin in southern Xinjiang, NW China are typical examples of this type (XETCAS, 1978). The alluvial fan in the Ejina basin is almost undissected. Compared the dissected and the undissected types of mountain-basin couples with the Tarim Basin, it possibly indicates that the alluvial sediments in the Ejina Basin are younger than those in the Tarim Basin, with alluvial sediments developed during late Pleistocene and Holocene.

3.3.4 Evidences from Palaeo-Riverbeds and Palaeo-Lakebeds

Palaeo-landscape evolution and climate change can also be deduced from direct evidences of preserved river terraces and high lake levels in the Ejina Basin. Numerous existing relics of the palaeo-riverbeds and palaeo-lakebeds in the Ejina Basin still can be identified clearly at larger scale than present both from the morphology in the field and from the remote-sensing images (Figures 2 and 13). It indicates that there have been large fluctuations in hydrological regime of the Ejina Basin during the part. According to the relic topography of the Ruoshui rive stem channel we can reasonably deduce that the terminal lake of the Ruoshui River should have been shifted from Gurinai to Juyanze, then to Sugunuoer and Gasunnuoer (Figure 2). Around these lake basins there are old lake terraces which are indicative of different lake levels. Taken lakebeds and lacustrine sedimentary profiles into consideration, it is possible to reconstruct lake level fluctuations from higher and lower lake levels in the Ejina Basin. Based on field investigation (Figure 6e) and geomorphological mapping of the Lake Sugunuoer depression, we calculated a high lake level of Sugunuoer at nearly 40 m above it present level. Along the southern shoreline of Guizihu three terraces are present. The highest terrace is ca. 40 m above the lake bottom. In the south of the Gurinai Lake basin the lake terrace lies 20 m above the bottom. Taking the bottom of Gushunnuoer as zero, around Sugunuoer and Juyanze the highest terraces are 34 m and 33.6 m above the bottom of Gushunnuoer respectively (Norin, 1980). As there are no basement mountains between Gushunnuoer and Sugunuoer, and there are lower topographic channels connecting Juyanze and Sugunuoer, it is reasonable to assume that these three lakes formed a unified single one during high level periods. The shells collected from the uppermost terrace of Sugunuoer were radiocarbon dated to 33,700±1300of the last glaciations (U-281; Norin, 1980).

Using radar wave data and Landsat images (TM, MSS), Guo et al., (2000) recognized a number of old river valley and lake basins buried by wind-blown sand in the north part of the Ejina Basin and the Alashan Highland. They delineated two parallel old drainage systems in the north and middle of the region and suggested that the moving sand belts mainly followed the old drainage courses. The old drainage verified that not only the Ejina Basin but also the Alashan Plateau was once a place occupied by many rivers and lakes in a warm and wet climate. Besides, the old drainage is NW-SE trending, not in accordance with the current south-higher-than-north and east-higher-than-west relief patterns. This fact indicates a relief reversion process caused possibly by neotectonic movement from Pleistocene epoch (Guo et al., 2000).

Palaeolake landscape evolution can also be in sighted from direct evidences of high lake levels in the Ejina Basin. Wunnemann et al. (1998) published results from sediments, lakeshore features and cores from Garsunnuoer and Sugunuoer lakes in the Ejina Basin, together with additional data from other locations. The chronology is based on 62 ^{14}C dates. Highest lake levels of +28 to +32 m occurred between 41 and ~33 ka in Garsunnuoer-Sugunuoer area. The lake level of Garsunnuoer was lowered 15 and 18 m at approximately 21 and 19 ka, respectively. Desiccation of Garsunnuoer-Sugunuoer area took place after 19 ka with dune sand accumulated continuously until 14 ka. In addition, no datable material has been found between 18.6 and 12.8 ka. This supports hyperarid conditions, due to a lack of organic material. A freshwater lake was established at Garsunnuoer-Sugunuoer area after 11.3 ka.

The eastern Juyanze palaeolake in the east edge of the Ejina Basin (Figure 13d) (41.75-42°N, 101.5-102°E) provides evidence of a complex hydrological pattern during the Holocene (Hartmann and Wunnemann, 2009). Lithological, geochemical and mineral data of sedimentary cores from the lake indicate remarkable difference between the early Holocene and mid to late Holocene lake formation. At about 10,700 cal BP fresh water lake formation starts with extreme run off events under a wet climate. Extremely low run off occurred between 8900 and 8100 cal BP. Compared with the early Holocene wet climate, the mid to late Holocene local rainfall was less pronounced and displays a general decreasing trend towards complete desiccation of the lake (Hartmann and Wunnemann, 2009). A two-meter deep hole (39.83°N, 102.47°E, Alashan) above 15 m than Lake Huhejilin water surface indicate that the lake level of Huhejilin was at least 15 m higher from about 8,000 to 7,000 cal BP than at present (Yang, 2001).

The studies of lake evolution in the central, eastern Alashan Plateau and the vicinity basins (Mongolia) principally support the glacial palaeoclimatic interpretation of landscape evolution presented so far. Based on lake level studies, Pauchur et al. (1995) and Wunnemann et al. (2007a, b) presumed that rainfall in Inner Mongolia was considerably higher between 39 ka BP and 23 ka BP, and in the time around 13 ka BP than at present. Lacustrine carbonate found in the vicinity of Lake Cheligeri (39.88°N, 102.25°E, Alashan) was ^{14}C dated to 32,150±4920 cal BP (Yang, 2001). The occurrence of lake was considered to be synchronous with the Anaglacial, likely to reflect the earliest appearance of extensive lakes in the central Alashan. Wunnemann et al. (2007a, b) suggests that a superlative 50,000 km^2 freshwater lake existed on the northwestern margin of the

Badanjilin Desert (Alashan) between 39 ka and 21 ka. During the period between 39 ka and 23 ka the climate in the Tenggeli Desert (Alshan) was also much more humid than at present (Pachur et al., 1995). About 33-23 ka BP there was a freshwater lake with an area of more than 16,200 km^2 and water depth of 25 m in the northwest of the present Tenggeli Desert (Zhang et al., 2002). The current Jilantai salt lake (39.74°N, 105.72°E, Alashan) was formed by the shrinkage of a vary large lake (Zhang et al., 2002). Geomorphologic, sedimentological and geochronological data obtained from the Darhad Basin (50.3-52°N, 99-100°E, Mongolia) confirmed that the Darhad sedimentary sequence has been formed since the Pliocene and represents a detailed archive of environmental changes due to a high content of lacustrine beds (Krivonogov et al., 2012). There have been two stages of deep lake in this basin. The first lake was dammed by a glacier during late MIS 5 (Krivonogov et al., 2005) or, alternatively, during early to middle MIS 3 (Gillespie et al., 2008). The second damming, glacial or sedimentary, formed another deep lake during MIS 4 or MIS 2. The Holocene history of the Darhad paleolake was kept at low levels, during which the lake was minimal or disappeared at ca 12-9.6 and after 4.5 ka cal. BP, relatively deep at 9.6-7.1 and 6.4-4.5 ka cal. BP and shallow at 7.1-6.4 ka cal. BP.

3.4 Mechanism of Landscape Development and Climatic Fluctuation during the Last Glaciations

Figure 15 gives a summary of the different morphologenic processes and the deferent palaeoclimatic evidence in the basins and mountains of Central Asia during the last 100,000 years. This framework for climatic fluctuations is derived from references on palaeoclimatic events in Northern China and Mongolia (e.g., Lehmkuhl, 1997; Owen et al., 1997; Benn and Owen, 1998; Lehmkuhl and Haselein, 2000; Grunert et al., 2000; Yang et al., 2004, 2006). The glacier fluctuations are based on results from Tibetan glaciers (Benn and Owen, 1998; Lehmkuhl and Haselein, 2000; Liu et al., 2002). In Tibet and the surrounding mountains maximum glacier advances, which promoted the landscape development of desert gorges and pediment, took place in both stages of the Last Glaciation (MIS4 and MIS 2, e.g. 70-50 ka and 32-15/14 ka) (Benn and Owen, 1998) and for the Late Glacial around 15 ka. For the MIS 3 there were several dates on higher lake levels showing wetter climatic conditions. In the southern parts of the Mongolia Altai, two moraines of the last glacial cycle can also be found (Grunert et al., 2000). This landscape-climate model provides a key clue to understand the mechanism of landscapes development and climatic fluctuation in the Ejina Basin during the last glaciations.

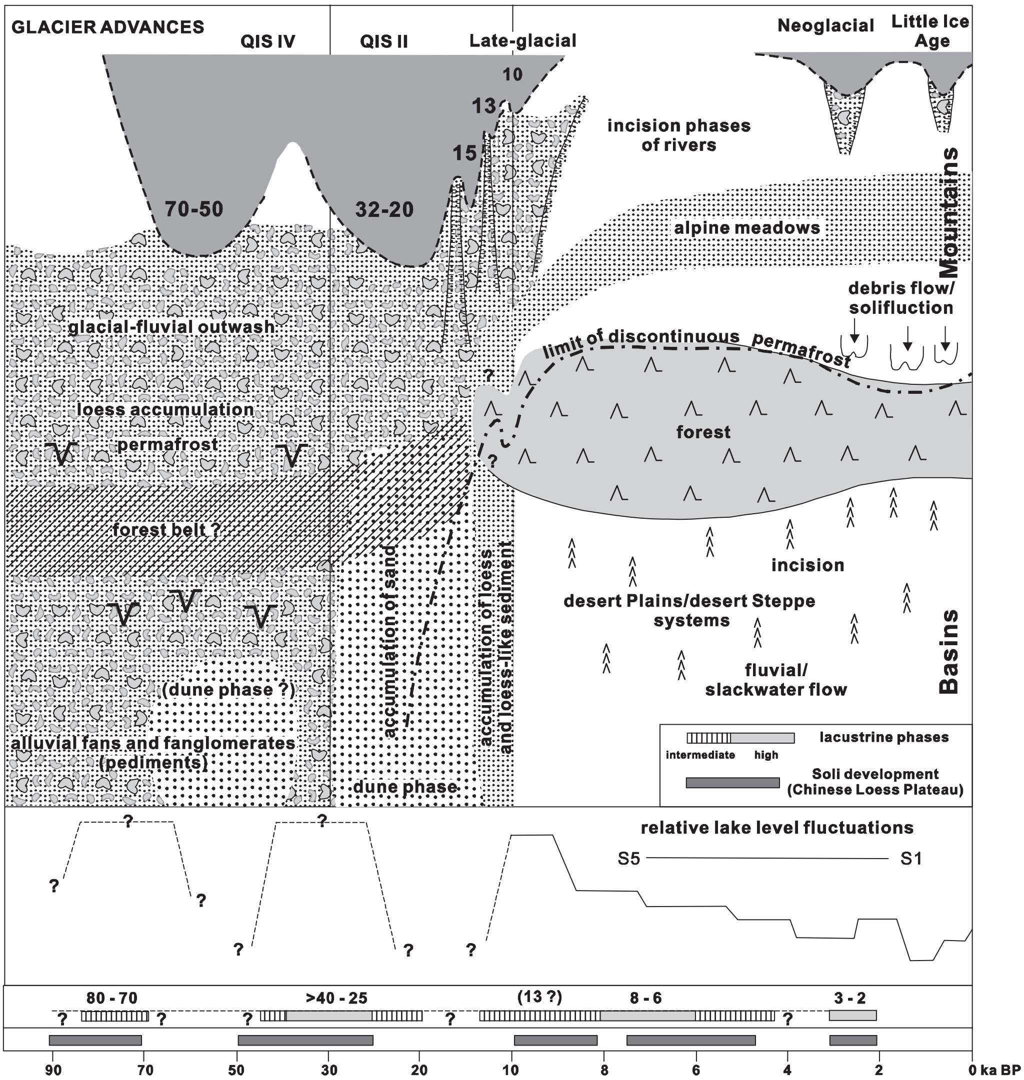

Figure 15. Landscape development including lake level changes, glacier fluctuations in the mountains (top) and basins (bottom) of northern China and Mongolia during the late Pleistocene (After Lehmkuhl and Haselein, 2000; Grunert et al., 2000)

The widespread distribution of Gobi desert of Central Asia originated mainly from alluvial fans and fanglomerates (pediment region). As shown in Figure 15 a transition from wetter (mainly MIS 3 and beginning MIS 2=Anaglacial period) to arid climatic conditions (OIS 2, Kataglacial period) occurred in most areas of Central Asia. Pollen and sedimentological evidence from western Loess Plateau indicates a smaller extent of the Gobi desert during cold and moist periods 73-60 ka and 27-19 ka and maximum expansion of the Gobi desert 60-50 ka and 19-10 ka (Feng et al., 1998). Observations on Late Quaternary alluvial fans in the Gobi of southern Mongolia (Owen et al., 1997) suggest that more humid conditions may have occurred between 40 and 23 ka followed by a period of increased aridity. Highest lake levels (28-32 m) occurred between 41 and ~33 ka in Garsunnuoer-Sugunuoer area (Norin, 1980; Wunnemann et al., 1998) of the Ejina Basin were related with higher levels of palaeoprecipitation and palaeohydrological cycle compared with present conditions.

In genesis, the increased precipitation in the western Inner Mongolia (Alashan and Ejina) during the last glaciation presumably originated from an increase of the westerlies (Yang et al., 2004). Benn and Owen (1998) also suggested that the glaciers of the northern Tibet and northern Karakorum responded to variations of the westerly winds during the Late Pleistocene. The Anaglacial time (ca. 32-24 ka) shows wetter conditions that could have been induced by an increase of the westerlies and a weakening of the winter monsoon (Lehmkuhl and Haselein, 2000). This first influenced the western part of Central Asia; the latter influenced the mainland of

China and the eastern part of Central Asia. During Kataglacial times (ca. 24-15 ka) a strengthening of the winter monsoon due to a significant displacement of the Siberia high-pressure to the south could have caused the dry climatic conditions in north and central China (An et al., 1991; Ding et al., 1995; Pachur et al., 1995). The different variations, especially in precipitation, might have been dominated by the dynamic and thermal effects of the Siberia High. This could provide a significant increase in the gradient of the wind and temperature fields, with the high-pressure cell becoming more persistent in the winter and springtime. During more humid periods in Central Asia this pressure system might be relatively weak and farther north, enhancing cyclonic precipitation by the westerlies or/and the monsoon in springtime.

High lake level is evidence that it was considerably wetter in the central Alashan in the early Holocene (Yang 2001; Yang et al., 2004). However, Eastern Juyanhai (Sugunuoer) record of pollen data does not show the early Holocene humidity maximum (Herzschuh et al., 2004), as suggested by the sedimentary data from monsoon-influenced areas of China (Figure 1b). These results indicate an extremely variable moisture availability in arid regions of Inner Mongolia during the entire Holocene. Owing to the interplay of the East Asian Summer Monsoon (EASM) with the westerly waves at the boundary of the summer monsoon limit, variations from dry to wet climate conditions seem to have been more pronounced than in other monsoon regions of China. We can assume that efficient local rainfall and, thus, surface runoff are mainly linked to the interplay of the EASM and the westerly waves, as they are today (Figure 1b). An intensification of EASM may result in a seasonal northward shift of effective moisture (An et al., 2000; Wunnemann et al., 2007a, b), with more frequent contact with the westerly waves, thus producing local heavy rainfall in the desert regions with a significant variability at intra-seasonal, inter-annual and inter-decadal time scales (Ding and Chan, 2005). The wet climate during early Holocene in northern China is also explained by an asynchronous Holocene optimum (HO) in China (An et al., 2000), as the HO reaching a maximum at different times in different regions, e.g., ca. 10,000-8000 yr ago in northeastern China, 10,000-7000 yr ago in north-central and northern east-central China, ca. 7000-5000 yr ago in the middle and lower reaches of the Yangtze River, and ca. 3000 yr ago in southern China.

4. Conclusion

The formation of landscapes depends mainly on internal and external dynamics. The internal dynamics, especially the tectonic movements since Mesozoic and Cenozoic era, are responsible for the general framework of the present mountain-basin coupled landscape in Ejina. External dynamics are predominantly regulated by climate factors, which induced the geomorphological diversity of the landscape in the Ejina Basin. Desert plains, pediments, desert gorges, aeolian dunes, rive channels and lakebeds are the main existing geomorphological units in the Basin. Our study shows that there are strong links between climatic geomorphological processes and landforms and the complexity is further heightened by human activity. The landscapes and the boundary of different landscape types in the basin have undergone changes or transformation. In the sense of climatic geomorphology, the old pediment in the region of present-day formation of the desert plains demonstrates higher precipitation and frost weathering processes of wetter and colder climate in the past. Desert gorges surrounding the peripheral highlands of the basin are relic of glacial and periglacial processes dissected by glacier water. Floods and strong wind are two major dynamic factors in the formation of Gobi desert. Small dunes are distributed widely along the Ruoshui river banks. Typical aerodynamic relief often occurs in the area with an average annual precipitation of less than 30 mm. The average annual precipitation at present is ca 35 mm in the Ejina Basin, indicating that landscapes of desert plain and aeolian dunes are contemporary landforms corresponding to the present climate. Relicts of old pediments and desert gorges indicate that the amplitude of precipitation variation in the past has reached 20 to 200 mm and this is much larger than present level. These suggest that the basin-scale forms of existing landscape studied are the result of glacial, periglacial, fluvial and alluvial action, aggradation and deggradational processes, as well as climatic changes. Previously studies have proved that the geomorphology of the central Alashan Plateau is dominantly a consequence of Quaternary climatic change that has forced environmental changes in the mountains and forelands. Evidences from the Ejina Basin further confirmed it and the landscape evolutions in the Alashan Plateau have been influenced considerably by external dynamics (climate) since the Pleistocene. Studies about the palaeo-lake level changes on the lowest marginal areas of the basin show that the regional aridity has changed during the last glaciation period and the regional climate has experienced high precipitation during ca. 39-23 ka BP and great fluctuations during Holocene. The periods of lower aridity occurred at ca 33ka B.P., 23 ka B.P., 10 ka B.P. and during the early and middle Holocene. Due to the quite weak Asian summer monsoon during the glacial times, the periods of lower aridity during the late Pleistocene would arise from a probably stronger influence of westerlies on the arid areas of the northern China and Central Asia.

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