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Solid Earth Discussions

Formation and dynamics of sandy dunes in the inland areas of the Hexi Corridor

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Abstract:

Dynamic changes of aeolian landforms and desertification under global warming in a middle-latitude desert belt, the Hexi Corridor in China, considered to be one of the source and engine area of sandstorms in China and Northern Hemisphere (NH), is a typical problem of climate change and landscape response, which need a comprehensive understanding of the history and forcing mechanisms of recent landform and environmental changes in the region. Based on the existing high-resolution satellite image interpretations, field investigations and observations, comprehensive evidences from geomorphological, aeolian-physical, granulometrical and geochemical analysis, this study discussed the formation of dune landforms, the mechanism of desertification and their environmental implications in the Hexi Corridor. The analytical results show that 80% of the sand particles flow within a height of 20~30 cm near the surface, and about half of the sand particles flow within a height of 0.3~0.5 cm near the surface in the Hexi Corridor. The average height of the typical crescent-shaped dunes is about 6.75m, and the minimum and maximum values are between 2.6 and 11.2m. On the inter-annual and multi-year time scales, only the crescent-shaped dunes and chains of barchan dunes are moving or wigwagging in the study area, while the parabolic and longitudinal dunes did not move. Under the influence of wind speed, strong wind days and other factors, the dunes at the edge of the Minqin Oasis move the fastest, with a moving speed of about 6.2m/a. Affected by the main wind direction and other factors, the dunes at the edge of the Dunhuang Oasis move the slowest, with a moving speed of about 0.8m/a. The main factors affecting the dynamic changes of sandy dunes in the Hexi Corridor are the annual precipitation, the annual average wind speed and the number of annual strong wind days, of which the annual precipitation contributes the largest, indicating that the climate factors have a most important impact on the dynamic change of sand dunes. The cumulative curve of particle size frequency of dune sediments in the Hexi Corridor basically presents a three-segment model, indicating a saltation mode dominated under the action of wind, but superimposed with a small amount of coarser and finer particles dominated by the creeping and suspension models, which is obviously different from that of the Gobi sediments with a dominant two-segment mode. The palaeo-geographical, sedimentological and geochemical evidences indicate that dune sediments in the Hexi Corridor are mainly derived from "locally or in-situ raised sandy sediments", which are mainly come from alluvial plains and ancient fluvial sediments, as well as ancient lake plains and lacustrine deposits,

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aeolian deposits in the piedmont denudation zones of the north and south mountains and modern fluvial sediments in the corridor. In geochemical compositions of major and trace elements, the dunes in the Hexi Corridor have certain similarities and differences to other sandy dunes in the northwest and northern deserts of China or aeolian loess in the Loess Plateau. Sandy dunes in the Hexi Corridor are relatively rich in iron and Co. Considering the proportion of fine particles on the surface, the coverage rate of surface salt crust, and the potential migration of erodible sandy materials, it can be concluded that the Gobi area in the west Hexi Corridor is not the main source area of sandstorms in the middle and east of the corridor, but the north probably is. In the past half century, the warming and humidification of local climate is the main cause of the reduction of sandstorms in the study area, and the Hexi Corridor has a potential trend of anti-desertification, which is mainly controlled by climate change but not human activities. For the oasis areas of the corridor, however, the effective measures to restrict desertification depend on human activities. Restriction of the decline of groundwater is the key to preventing desertification in oases, rather than water transfer from outer river basins.

Keywords:
Sandy dunes; Geomorphology; Sedimentology; Geochemistry; Desertification; Hexi Corridor.

1. Introduction

Aeolian sediments and their sedimentary strata record the environmental changes in the source areas or desert areas and their responses to global climate change and human activities. They are unique and important sedimentary and geomorphological archives of dryland landscape evolution (Goudie, 2002; Lancaster et al. ., 2013, 2016; Williams, 2014; Yang et al., 2019). In China, about 566,000 square kilometers of land area are covered by aeolian sand, covering a wide range of geomorphological and tectonic backgrounds ranging from 155m below sea level to 5,000m above sea level (Yang, 2006). The desert landscapes dominated by active sandy dunes are mainly distributed in the arid areas with an average annual precipitation of less than 200 mm, while the sandy-land landscapes dominated by semi-active dunes and vegetated dunes mainly appeared in the semi-arid areas with an average annual precipitation of 200-400 mm (Zhu et al., 1980). The present geomorphology of these sandy deserts is the product of long-term and short-term changes of the interaction between endogenic forces (such as tectonic movement) and external forces (such as climate) of the earth system. In turn, these deserts may directly affect the global climate system through sediment circulation (such as dust cycles) (Yang, 2006). Therefore, the understanding of desert landscape evolution will increase our understanding of the earth system.

Regarding the formation and evolution of desert landscapes in China, the loess-paleosol sedimentary

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sequences from the Loess Plateau indicate that the deserts in northwest China may have existed as early as 22 myr (Guo et al., 2002, 2004), but the geomorphological and sedimentological evidences found inside these deserts indicate that the modern-scale landscapes of these deserts are much younger in age (Yang et al., 2004, 2006). But up to now, due to the lack of long-enough and continuous stratigraphic profiles, the geomorphological connection between the Tertiary desert and the present desert is still unclear. And in many areas of the deserts in northwest China, lacustrine and fluvial sediments from the Late Pleistocene and even Holocene are buried under the sandy dunes, which indicate that the environment of these desert areas has changed dramatically during the late Quaternary (Yang, 2006; Chen et al., 2020). For example, in the Badanjilin Desert near the northeast of the Hexi Corridor in China, although the formation mechanism of the giant sandy dunes in the desert is still a dispute in people's understanding, such as "the theory of climate control", "the theory of tectonical/geomorphological control" and "the theory of groundwater control", geomorphological survey is essential to resolve this dispute. It is conceivable that the dynamic genesis of sand dunes, namely desertification, will be crucial for understanding this problem, where the dune landforms and desertification processes cover almost all the important information archives that understanding the earth system.

The movement of aeolian materials and related formation, dynamics and evolution of dune landforms are the results of the transportation and accumulation of sandy sediments under the influence of climate (especially wind and atmospheric circulation), which is the direct cause of landsurface desertification and one of its important manifestations (Zhu et al., 1980; Zhu and Wang, 1992; Yang et al., 2004, 2019). For example, the ruins of ancient cities are buried by shifting sands in northern China and some famous steppes in history but are occupied at present by desert landscapes with undulating sandy dunes, which are clear evidences of land desertification in the past 2 Ka (Zhu and Wang, 1992). The movement of sand dunes not only affects the development and safety of agriculture and transportation, but also reflects the modern geomorphological processes of landform development in arid areas and its environmental response to global changes. Therefore, it is of great significance to study the formation and dynamic characteristics of various dune landforms in different regions of the world to reveal desertification and environmental changes in drylands.

The formation and dynamics of sandy dunes in the world were observed and studied for the first time in the United States (Finkel, 1959) and the former Soviet Union (Znamenski, 1962) in the 1950s. During this period, the famous desert physicist Bagnold put forward the formation mechanism of mobile sandy dunes and the formula of moving velocity of active dunes (Bagnold, 1959). Dune formation and dynamics in China were qualitatively or semi-quantitatively described in most early studies (Yang, 2006). For example, some pioneer scholars have studied the development and movement of sandy dunes in the Taklamakan Desert, and they quantitatively analyzed the moving speed and evolution process of local crescent sandy dunes (Zhu et al., 1964; Zhu et al., 1980, 1981). However, these studies still laid a solid foundation for the

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later development of refined and quantitative researches due to the progress of research methods and technical tools, and they are still a milestone cornerstone of desert researches in China.

The Hexi Corridor in northwestern China at the middle-latitudes of Northern Hemisphere (NH) was once one of the most important trunk sections of the world-famous Silk Road, and also a place where several ancient cultures converged. However, today it is facing severe problems of desertification and climate change under global warming. For nearly half a century, frequent sandstorms in northern China have been considered to be the notorious tragedy and direct consequence of the desertification in the Hexi Corridor, because the Hexi area is considered to be the main source area and the engine area of sandstorms in China (Zhang and Ren, 2003; Pu, 2005; Li and Zhang, 2007). Therefore, the problem of desertification in the Hexi Corridor is one of the major problems that have been urgently needed to be resolved in Gansu Province and even in northern China for half a century.

The purpose of this study is, based on the comprehensive evidences from the extensive dune geomorphological survey, the sedimentological and geochemical analysis of dune sediments, and the meteorological analysis of local weather records in the past several decades, to understand the genesis and dynamic changes of sandy dunes in the Hexi Corridor and its relationship with climate change during the past half century, and to explore the mechanism of local desertification in the Hexi Corridor and its environmental implications.

2. Background and analytical methods

2. 1. Geographical, geological, geomorphological and hydrological backgrounds of the Hexi Corridor

The Hexi Corridor is located in the central and western parts of Gansu Province in Northwest China (Fig.1), including Wuwei, Jinchang, Zhangye, Jiuquan, Jiayuguan and other cities in the west of the Yellow River, with a total area of approximately 5,100 square kilometers. In terms of regional geomorphology, the Hexi Corridor is located in the lowland area between the Qilian Mountains and the Alashan Plateau. The Alashan Plateau in the north of the Hexi Corridor distributes three large sandy deserts of China, i.e. the Badanjilin Desert, the Tenggeli Desert and the Ulanbuhe Desert. For the Qilian Mountains in the south of the Hexi Corridor, the melting water of ice and snow in the Qilian Mountains in the south converges into several large rivers flowing northward into the Hexi Corridor, such as the Heihe River, the Shiyang River and the Shule River, etc. In the middle and lower reaches of these rivers flowing through the south corridor, diluvial and alluvial fans are well developed, and hydrologically, they are also the main locations of spring overflow zone of each catchment derived from the Qilan Mountains. Oases are widely developed in the toes of these alluvial fans and are the major agricultural exploitation areas and the resident agglomeration areas of northwest China.

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In climate, the Hexi Corridor is located in the center of temperate desert belt in the mid-latitudes of Northern Hemisphere. Except for the forest and grasslands distributed in the middle- and high-elevation mountain areas in the south, most of the Hexi Corridor is under a typical arid desert climate with desert landforms developed. The desert types are dominated by Gobi desert and sandy desert, which account for 46.64% of the total area of the region.

In history, the Hexi Corridor was a necessary place for the famous ancient Silk Road in China. In modern times, however, the expansion of population and socio-economic development of the Hexi Corridor, as well as the human-caused competitive redistribution of water resources, have led to the onset and enhancement of desertification in the Hexi Corridor (Pu, 2005). The expansions of sandy dunes and dune fields in the corridor, and even the combination with surrounding sandy desert, have occurred in the past 2 ka (Zhu and Wang, 1992; Ren et al., 2014).

In terms of aeolian landforms, sands dunes or dune fields in the Hexi Corridor are mainly distributed in a narrow and long belt between the Qilian Mountains and the Heli mountains to the west of Wushaoling and the east of Palaeo-Yumenguan (Fig. 2) (Zhu et al., 1980). Compared with the dune landforms in the adjacent areas of the Badanjilin and Tenggeli Deserts, the sandy dunes in the two deserts tend to be convergent in spatial distribution, while the Hexi Corridor is different, where the dunes are almost scattered, mainly distributed in the vicinity of oases along some rivers, in the oasis or Gobi desert areas (Fig. 2). From east to west in the dune belt, sand dunes are mainly distributed around the Minqin Oasis in the lower reaches of the Shiyang River, the Zhangye and Gaotai oases in the middle reaches of Heihe River, the Jiuquan and Jinta oases in the lower reaches of the Beidahe River, and the Dunhuang oasis in the lower reaches of the Danghe River (Fig. 2) (Zhu et al., 1980).

The total area of dune fields in the Hexi Corridor is about 754 square kilometers, and a large number of big crescent-shaped dunes and chains of crescent-shaped dunes develop on the edges of oases. The Minqin Basin is a typical area with dune landforms development in the Hexi Corridor. It is located at the lower reaches of the Shiyang River and the western edge of the Tenggeli Desert. The annual average precipitation is about 116.4 mm and the annual average wind speed is about 2.25 m/s. A large number of crescent-shaped sandy dunes are distributed on the northwestern edge of the oasis, i.e., the windward of sand-transport winds in the oasis.

2. 2. Data and analytical methods

For the study of sandy dune geomorphology, the first method is to use the sample-quadrate survey procedure to measure the height and shape of typical high dunes in the field with a rangefinder, and the second is to measure the length, angle and width of the windward slope and downwind slope of each dune in the sample quadrate and between different quadrates along the local dominant wind direction by

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using rangefinder and remote sensing image scales (such as Google Earth scales, etc.), and then the comprehensive geomorphic data of sandy dunes in the region is obtained. In addition to the geomorphological data of sandy dunes themselves, landscape researchers will also use the sample-quadrate survey method to investigate the ecological parameters of vegetation cover in the selected sampling area. For both geomorphological and ecological surveys, sub-scale sample quadrates will be selected from the upper, middle and lower parts of the windward and leeward slopes of each dune. Three quadrates can be selected from the dune slope in the windward and downwind directions of each dune along the local prevailing wind direction and the size of each quadrate can be designed as 5m × 5m or smaller (Chang et al., 2016a, 2017; Lang et al., 2017).

In recent years, a number of studies have been systematically carried out in different areas of the Hexi Corridor to investigate the different landform types of widespread sandy dunes at a geomorphic unit scale in the field, including the crescent-shaped (barchan) dunes, chains of barchan dunes, pyramid-shaped dunes, parabolic dunes and longitudinal dunes belt. Based on field observations and satellite remote sensing image data in different periods, the geomorphological parameters and characteristics of these dunes are obtained (Zhang and Dong, 2014; Chang et al., 2016a, 2017; Lang et al., 2017). The geomorphological parameters of part of these dunes in the Hexi Corridor and their comprehensive data are shown in Tables 1 and 2.

In addition to the above-mentioned intuitive survey and measurement of geomorphic parameter of sandy dunes, quantifying the structure of wind-blown sand flow and the movement rate of dunes is also the most direct and effective means to explain the dynamic change of dunes and their geomorphological evolution (Dong et al., 1998; Chen and Liu, 2011; He et al., 2012; Dong and Huang, 2013; Wang et al., 2013; Hu et al., 2016; Mao et al., 2016). Generally, there are two methods to study the moving velocity of sandy dunes, one is early positioning observation (MDCES, 1975; Dong et al., 1998; He et al., 2012) and the other is based on remote sensing images (Chen and Liu, 2011; Dong and Huang, 2013; Mao et al., 2016). Research works based on the both methods have been carried out in dune fields of the Hexi Corridor. On this basis, this study will integrate and organize the different observation data of dune movement measurement in the Hexi Corridor, and further discuss the geomorphological evolution of sandy dunes in the Hexi corridor.

The grain size composition and distribution of aeolian sediment is an important indicator to understand the formation and development of sand dunes. This is because the grain size parameters of sand particles can be used not only to distinguish the depositional environment (aeolian, fluvial or lacustrine), but also to identify the movement types (creep, saltation or suspension) of sediments in the transportation process. Therefore, the analysis and study on the granular sedimentology of sandy dunes is a basic method to understand the genesis and evolution of the dunes in the Hexi Corridor. At present, research works about the grain-size sedimentology of aeolian sediments and related aqueous sediments,

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such as alluvial and proluvial fans, lacustrine deposits, fluvial deposits, has been widely carried out in the Hexi Corridor (Zhu and Yu, 2014; Zhu et al., 2014; Zhang and Dong, 2015; Zhang et al., 2016; Pan et al., 2019; Zhang et al., 2020). On this basis, this study systematically collects and organizes the granular evidences, which makes it possible to conduct a comprehensive and comparative study on the dunes in the Hexi Corridor from a perspective of sedimentology.

Erodible clastic sediments as the material sources are the fundamental base for the formation of sedimentary landforms (Pettijohn et al., 1972; Taylor and McLennan, 1985). Therefore, identifying the source of wind-induced materials in an arid environment is a prerequisite for understanding the formation of dune landforms (Zhu et al., 1980, 1981; Yang et al., 2012). The analysis of major and trace elements, including rare earth elements, has become a reliable technique for detecting the source of desert sediments (Muhs et al., 1995, 1996; Pease et al., 1998; Honda and Shimizu, 1998; Wolfe et al., 2000; Pease and Tchakerian, 2003; Zimbelman and Williams, 2002; Muhs, 2004; Yang et al., 2007; Zhu and Yang, 2009; Jiang and Yang, 2019). The reason is that for aeolian sediments, the differences in compositions and distributions of rare earth elements and other trace elements in different samples/sub-fractions are largely controlled by the parent-rock compositions, because these elements only exist in specific minerals and are difficult to be lost during transportation (Pettijohn et al., 1972; Taylor and McLennan, 1985). In the Hexi Corridor, preliminary results have been achieved in the case studies of analyzing the elemental compositions of aeolian sediments using major- and trace-element geochemical methods (e.g., Ren et al., 2014; Pan et al., 2019; Zhang et al., 2020), which provide basic data for this study to comprehensively identify the material sources of different dunes in the study area.

The continuous data records of different meteorological parameters of local weather stations in the Hexi Corridor in the past half century, such as temperature, precipitation, relative humidity, wind speed, strong wind days and sandstorms days, will not only be the basis for this study to discuss the regional climate change under the background of global warming, but also the basis for exploring the response of regional landscape to climate change based on the statistical relationship between geomorphic parameters and climate parameters on a multi-decade time scale. Therefore, this study will collect and use the meteorological data of the Hexi Corridor for nearly half a century to analyze the regional climate change and its relationship with the dynamic changes of dune landforms.

3. Results

3. 1. Geomorphological parameters (Height, shape, and dynamics) of sandy dunes in the Hexi Corridor

The comprehensive data on the heights of different types of sandy dunes widely developed in different areas of the Hexi Corridor, as well as other geomorphic parameters of these dunes, can be found

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in Table 1, Table 2 and Fig. 3. It can be seen from Table 1, Table 2 and Fig. 3 that the average height of typical crescent-shape (barchan) dunes in the Hexi Corridor is about 6.75m, the maximum is about 11.20m, and the minimum is only about 2.60 m. The average height of typical chains of barchan dunes in the study area is about 9.23 m, the maximum is about 13.80 m, and the minimum is only about 5.80 m. The typical pyramid-shaped dunes in the study area have an average height of about 86.25 m, with a maximum of about 121.80 m and a minimum of about 25.80 m. The average height of typical parabolic dunes in the study area is about 4.08 m, the maximum is about 4.60 m, and the minimum is only about 3.38 m. The average height of typical longitudinal dunes in the study area is about 13.02 m, the maximum is about 18.60 m, and the minimum is only about 5.60 m.

Regarding the dynamic changes of sandy dune landforms, as early as 1959-1964, the newly established Minqin Comprehensive Experimental Station of Desertification Control (MCESDC) in China carried out the field positioning observation and research on wind-blown sand flows in the Hexi Corridor (Zhu et al., 1980; Zhu, 1994, 1999; Zhu and Wang, 1992; Wang, 2003). For example, 187 positioning observation points were set up in field along a 20km long observation line in the Minqin Basin and a large number of observations were made to assess the structure of wind-blown sand flow, the shape of sand dunes, erosion and accumulation of aeolian sand, changes in sand ripples and sand dune movement, etc. Later works continued to carry out relevant researches on different areas of the Hexi Corridor (MDCES, 1975; Zhu et al., 1980; Wang, 2003; Zhang et al., 2004; Qu et al., 2005; Wang et al., 2013; Yin et al., 2014, 2016; Chang et al., 2016a, 2017; Zhang et al., 2016; An et al., 2019; Chang, 2019; Hu et al., 2020). Results of these studies show that in the Hexi Corridor, 80% of the sand particles of the wind-blown sand flows are moving in the height of 20 ~ 30cm near the ground surface, of which about half of the sand particles are moving in the height of 0.3 ~ 0.5cm near the surface. At the wind speed of 7m/s, 75% of the sand particles are within the height of 10cm, and only 0.035% are within the height of 76 ~ 200cm. The movement modes of sand particles in the Hexi Corridor include creeping (wriggling/rolling), saltation (jumping/springing) and suspension (floating/levitating), and the movement modes of sandy dunes include three ways: straight-forward movement, wigwagging movement, and onward-wigwagging movement (Wang, 2003).

Among the different sandy dunes in the Hexi Corridor, the crescent-shaped (barchan) dunes, chains of barchan dunes, pyramid-shaped dunes, parabolic dunes and longitudinal dunes have received the most extensive attention. Based on field surveys/measurements (e.g. measurement of the electronic total station) and satellite image (e.g. Google Earth) data of different periods, the researchers obtained the geomorphological parameters and moving speeds of these different dunes (e.g. Ren et al., 2010; Chang et al., 2016a), as shown in Table 1 and Fig. 3.

It can be seen that the average moving speed of the crescent-shaped dunes is about 6.62 m/a, the maximum is 12.51 m/a, and the minimum is only 1.01 m/a (Fig. 3a). The average moving speed of the

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chains of barchan dunes is about 6.54 m/a, the maximum is 8.30 m/a, and the minimum is only 5.34 m/a (Fig. 3b). Compared with the crescent-shaped dunes, the chains of barchan dunes move relatively slowly and the movement speed changes little. In general, the crescent-shaped dunes and the chains of barchan dunes in the Hexi Corridor move along the NW-SE direction. The direction of movement of the east part of the corridor is about N45° W, while the movement angle of the Jinta area in the western corridor increases (Table 1 and Fig. 3). The average swing velocity at the tops of the pyramid dunes is about 6.32 m/a, the maximum is 97.37 m/a, and the minimum is only 1.14 m/a. The direction of movement of the pyramid dunes will also change, but its main direction of motion is SW-NE (Fig. 3).

3. 2. Granular sedimentology of sandy dunes in the Hexi Corridor

In the Jiuquan Gaotai area in the middle and Eastern Hexi Corridor (area B in Fig. 2), grain size parameters (including mean, standard deviation, skewness and kurtosis, etc.) of sand dunes at different geomorphological positions on the dune surface, such as the toes of windward slope, slope surface, dune crest (top), toes of leeward slope, were determined (Zhang and Dong, 2015). The granular sedimentology shows that the grain-size frequency cumulative curves of sand dunes in this area are mostly unimodal, and a few are bimodal (Fig. 4); the dune surface sediments are mostly fine sand fraction and very fine sand fraction, with an average grain size of 0.07 mm±0.01～0.24 mm±0.06, which is similar to the average particle size of sand dunes in the world. The finer the dune particle is, the better the sorting degree is. The mean grain size increases with the increase of the skewness values, but decreases with the increase of the kurtosis values. From upwind to downwind, the dune sediment becomes finer, the medium-sand fraction decreases, and the fine-sand fraction, very-fine-sand fraction, silt-fraction and clay-fraction increase; the source materials affect the changes in the average grain size of dune sediment from upwind to downwind (Zhang and Dong, 2015). In this dune field, there are three types of grain-size-distribution patterns in a dune-scale unit: the dune crest is coarser (the dune slope and inter-dune area are finer), the dune crest is finer (the dune slope and inter-dune land are coarser), and there is no significant difference between dune crest, windward and leeward slopes. Among them, the coarser-dune-crest model is the most common type, accounting for 69% of all sandy dunes, while the finer-dune-crest is the second most common type (accounting for 24%) (Zhang and Dong, 2015).

In the Jinta-Jiayuguan-Huahai area in the western Hexi Corridor (area A in Fig. 2), the crescent-shaped (barchan) dunes developed on the Gobi desert and ancient playas have been systematically studied on granular sedimentology (Pan et al., 2019). The results of this research show that the grain size of the surface aeolian sediments of crescent-shaped dunes in the western Hexi Corridor is mainly the medium-sand fraction (21.7～57.4%), followed by the fine-sand fraction (23.2～53.0%); the mean grain

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size ranges between 0.27～0.43 mm (while the paleolacustrine sediment ranges between 0.10～0.21 mm) (Pan et al., 2019). The crescent-shaped dune sediments in this region are mainly medium to good in the sorting level. The frequency cumulative curves of dunes are mostly unimodal and nearly symmetrical, and the kurtosis is medium in level. The granular characteristics of sand dunes in this region are closely linked to their dune morphology and the properties of the underlying Gobi surface (Pan et al., 2019).

3. 3. Geochemical and sources of dune sediments in the Hexi Corridor

Regarding the source of aeolian sediments, the provenance of sandy dunes in the Hexi Corridor was firstly investigated as early as 1959-1964 by the China's Minqin Comprehensive Experimental Station of Desertification Control (MCESDC) (MDCES, 1975; Zhu et al., 1980; Chang, 2019), and continues to this day (Ferrat et al., 2011; Ren and Wang, 2010; Ren et al., 2014; Zhang and Dong, 2015; Zhang et al., 2016, 2020; Chang, 2019).

Due to the application of geochemical methods in recent years, it is possible to identify sediment sources more precisely (Wang, 2011; Wang and Wang, 2013; Ren et al., 2014; Pan et al., 2019; Zhang et al., 2020). In this study, based on geochemical evidences, we take the Gobi areas in the Huahai-Jiayuguan-Jinta region of the west Hexi Corridor (area A in Fig. 2), the Jinta-Gaotai region of the middle Hexi Corridor (area B in Fig. 2) and the Minqin Basin in the east Hexi Corridor (area C in Fig. 2) as the case examples (Ren et al., 2014; Pan et al., 2019; Zhang et al., 2020) to explore the material sources of sandy dunes developed in these regions.

The Minqin Basin is dominated by an oasis landscape. It is located in the east Hexi Corridor (area C in Fig. 2), and the northern edge of the Loess Plateau, and is bordered by the Badanjilin Desert to the northwest and the Tenggeli Desert to the southeast (Figs. 1 and 2). The Minqin Basin is considered a natural obstacle to the convergence of the two deserts (Zhu et al., 1980). Geographically and geomorphologically, identifying the origin and transportation of aeolian sediments in the Minqin oasis and its adjacent desert areas will help to better understand the relationship between loess and desert in China (Liu, 1985; Sun, 2002; Yang et al., 2007a; Yang et al., 2011; Ren et al., 2014).

The research works of Ren et al., (2014) and others (Ren, 2010; Ren and Wang, 2010) systematically collected aeolian sediment samples from sandy dunes in the Minqin Oasis and its surrounding desert areas. Through geochemical analysis, combined with wind data and cluster analysis methods, the characteristics of compositions and spatial distributions of major and trace elements of aeolian samples from the Minqin Oasis and its adjacent deserts (the Badanjilin and Tenggeli Deserts), as well as the provenance and transportation pathways of aeolian sediments in these areas, were discussed. The analysis of geochemical data shows that in the bulk (whole-rock) samples of sandy dunes in the Minqin Basin (M) and its

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surrounding areas (the Badanjilin Desert B, the Badanjilin-Minqin transition zone BM, the Tenggeli-Minqin transition zone TM, the northeast edge of the Tenggeli Desert TNE, the southwest edge of the Tenggeli Desert TSW), the contents of major elements are higher in the content of SiO_2, reaching between 72.2% and 88.9% with an average of about 83.3%. In contrast, the contents of most trace elements are relatively low, and only the contents of Ba, Ce, Co, Mn and Sr reach > 100 ppm (Ren, 2010; Ren et al., 2014). Compared with the average composition of the upper continental crust (UCC, Taylor and McLennan, 1985), the concentrations of Ba, SiO_2, Rb, Sr, Al_2O_3 and K_2O in the Minqin Basin and its surrounding areas are relatively uniform (Fig. 5), indicating that the spatial differences of these elements in abundance are small and they are relatively homogeneous in the study area, while obvious convex and concave shapes are observed for other elements (Fig. 5), indicating that the spatial differences of these elements in abundances are large and they are relatively heterogeneous in the study area. The homogeneous and heterogeneous characteristics between different elements thus can be used as geochemical indicators to identify different sources of sediments in the study area. For the major elements' compositions, only SiO_2 is enriched relative to UCC, and the others are relatively depleted (Fig. 5). For the trace elements' abundance, most elements are depleted, except for Cr and Ni enriched in B and BM area and Cr enriched in TNE area. The binary and ternary diagrams of some major and trace elements and their ratios, such as Cr, Ni, Cr/V, Y/Ni, Al, V, Zr, Hf, Zr/Hf, reveal that sandy dunes have different material sources between the western part of the Minqin Basin (including sub-area B, BM and TNE) and the southeast side of the Minqin Basin (TSW), while sand dunes in the Minqin Basin (M) and the Tenggeli-Minqin transition zone (TM) are related to the two big deserts, respectively (Ren et al., 2014).

Some researchers have conducted geochemical analysis of major and trace elements in aeolian sediments of barchans dunes and other sediments developed in the western Hexi Corridor (Zhang et al., 2017; Pan et al., 2019). The dunes studied are located in the Gobi area to the north and west of Jiayuguan (area A in Fig. 2). The dune types are mainly barchan dunes, chains of barchan dune and asymmetric barchans dunes (Zhang et al., 2017; Pan et al., 2019). The aeolian samples were mainly collected from the surface sediments of barchan dunes and asymmetric barchan dunes, including different geomorphic sites of dunes such as the crest of dune, the bottom of the windward slope, the middle of the windward slope, and the bottom of the leeward slope. The analytical results show that after the standardization of UCC, the barchan dunes on the Gobi surface in the western Hexi Corridor are significantly enriched in the major elements CaO and SiO_2 (accounting for 5.55% and 66.12% of the total rock mass, respectively). The element contents of Cao, MgO and Fe_2O_3 are gradually enriched from northwest to Southeast, that is, the enrichment degree increases along the dominant wind direction. The UCC-normalized concentrations of Na_2O and K_2O are both significantly <1, indicating that alkali metal elements are significantly depleted or leached in the study area (Zhang et al., 2017; Pan et al., 2019). The contents of trace elements vary among different dune samples, reflecting a complexity of provenance of these dune sediments; however, the

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variations of trace elements are similar in different geomorphic positions of the one dune (Pan et al., 2019). Compared with UCC, trace elements Co, As, La, and Nd are significantly enriched, while other elements are depleted. Compared with the chemical elements in the Tenggeli and Badanjilin Deserts (Li, 2011), the Hexi Corridor has lower SiO_2 content, similar K_2O content, and lower contents of other trance elements.

Mineralogical and major- and trace-element geochemical analyses of aeolian sediments from the Jinta-Gaotai area (area B in Fig. 2) in the middle Hexi Corridor have been carried out (Ferrat et al., 2011; Wang and Wang, 2013; Wang et al., 2018; Zhang et al., 2020). These studies use the light/heavy mineral assemblages, the ratios of Na_2O/Al_2O_3 to K_2O/Al_2O_3 and SiO_2/Al_2O_3, Ba/Sr to Rb/Sr, Rb/Sr to Ce/Sr, and the composition of CaO and Cl to identify the provenance of aeolian sediments in the study area. Similar mineralogical compositions (mica, quartz, illite, muscovite and albite) are found in dune sediments from the Hexi Corridor and adjacent areas such as the Tenggeli and Badanjilin Deserts (Ferrat et al., 2011). This feature is also found by major and trace element analysis (Wang and Wang, 2013; Zhang et al., 2020), indicating that the geochemical characteristics of aeolian sediments in the Hexi Corridor and its adjacent areas are also similar. Compared with the composition of the upper continental crust (UCC), dune sediments in the Jinta-Gaotai area in the middle Hexi Corridor are also enriched in CaO (Fig. 6). Through the methods of multi-dimensional scaling (MDS), principal component analysis (PCA) and regional topography analysis, these studies suggest that the Hexi Corridor is not only the sediment sink of the Qilian Mountains, but also the sediment sink of the Beishan Mountains. The sandy dunes from the Hexi Corridor are similar in provenance to those from the Tenggelil, Badanjilin, and Kumtag Deserts (Zhang et al., 2020).

4. Discussion

4. 1. Physiochemical characteristics of sandy dunes in the Hexi Corridor

The above analytical results of geomorphological parameters indicate that in the dynamic process of different dunes in the Hexi Corridor, the crescent-shaped dunes move the fastest, followed by the chains of barchan dunes; only the top of the pyramid dunes wigwags, while the parabolic dunes and the longitudinal dunes hardly move forward; the higher the height of the crescent-shaped dune (or the chain of barchan dunes) is, the slower their movement is; on the contrary, the higher the height of the pyramid dunes is, the faster they swing. Analysis also suggests that the moving speed of sandy dunes is positively correlated with the average wind speed of sandstorms.

Here, we compare the moving speed of sandy dunes in the Hexi Corridor with that in other desert areas in northwest China. For example, the observation results of eight crescent-shaped dunes along the oil transportation highway in the Taklamakan Desert show that the moving speed of sandy dunes in October 1991～1992 is 4.81～10.87 m, with an average of 7.29 m; the moving speed of sandy dunes in

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October 1992～1993 is 3.33～8.89 m, with an average of 5.56 m (Dong et al., 1998). Regarding the analytical results based on high-resolution remote sensing images in 2010～2014, the average speed of dune movement in the Tenggelish Desert was 4.36 m/a in 2010～2013, and was 2.43 m/a in 2013～2014 (He et al., 2016). For the research about the movement of crescent-shaped dunes in the Maowusu Sandy Land based on Google Earth images (Wang et al., 2013), the moving speed of sandy dunes in the study area is between 3.5 and 9.5 m/a; the width of the dunes is significantly correlated with the horizontal length of the leeward slope; the width of the dune and the horizontal length of the leeward slope decrease during the movement of dunes, while the horizontal length of the windward slope increases; there is a good correlation between the moving speed and the width of the dune.

Compared with the dynamic process of sandy dunes in different deserts mentioned above, the crescent-shaped dunes widely distributed on the edge of oases in the Hexi Corridor also have obvious spatial differences in dynamic changes. For example, during the period 2006～2015, due to the influence of wind speed, strong wind days and other factors, the sandy dunes at the edge of the Oasis in the Minqin area moved the fastest, with a moving speed of about 6.2m/a; affected by the main wind direction and other factors, the sandy dunes at the edge of oasis in the Dunhuang area moved the slowest, with a moving speed of about 0.8m/a; under the influence of different meteorological factors, the horizontal length of the windward slope of sandy dunes in most areas of the Hexi Corridor increased in 2015 compared with 2016, while the horizontal length of the leeward slope decreased. There are three main factors influencing the dynamic changes of sandy dunes in the Hexi Corridor, i.e. the annual precipitation, the annual average wind speed, and the annual strong wind days, among which the annual precipitation has the largest contribution rate (Shi et al., 2018). It can be concluded that meteorological factors (or climate factors) have an important impact on the dynamic change of sandy dunes in the Hexi Corridor, and this impact has both positive (promoting) and negative (inhibiting) effects.

The above analytical results of granular sedimentology of aeolian and aqueous sediments (alluvial and proluvial fans, lacustrine and fluvial deposits, etc.) from the Hexi Corridor have shown that sand dunes have different grain size compositions in different regions of the Hexi Corridor. This is also confirmed by many previous works (Zhu and Yu, 2014; Zhu et al., 2014; Zhang and Dong, 2015; Zhang et al., 2016; Pan et al., 2019; Zhang et al., 2020). The spatial differences in grain size compositions reflect the different depositional environment, the different sources and the different transportation modes in the formation and development of sandy dunes in the Hexi Corridor.

Based on the Sahu (1964) discriminant function, the sedimentary environment in the middle and eastern part of the Hexi Corridor includes three types of deposits, i.e., aeolian deposit, lacustrine deposit and alluvial-proluvial deposit, of which aeolian deposit is the dominant (about 50%) (Zhang and Dong, 2015).

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It is obvious that the average grain size of sand dunes in of the western Hexi Corridor (such as the Jiaquan-Jinta area) is larger than that in the central-eastern Hexi Corridor (such as the Jiuquan-Gaotai area) and also larger than those in other desert regions of northern China. Compared with the crescent-shaped dunes in the central-eastern Hexi Corridor, the top of shrub dunes in the western Hexi Corridor is dominated by the medium- to fine-sand fractions, but not the medium-sand fraction. This is possibly because of the wide distribution of gravel around the shrub dune, which reduce the airflow velocity near the ground, making it difficult for the coarser-grained particles to move up to the surface of shrub dunes. While for the crescent-shaped dunes, the length of wind flow path on the windward side of the dune is longer. During the long-distance movement of the unsaturated aeolian sand flow, the coarser-grained particles collide with the ground surface elastically, resulting in the coarser-grained particles moving to a higher position on the windward slope of crescent-shaped dune, so the crescent-shaped dunes are dominated by the medium-sand-fraction particles. The clay-grain content is less in the surface layer of crescent-shaped dunes and shrub dunes, but more (up to 28.2%) in sandy dunes developed on dry lake beds (playas) or ancient lake area, which is relevant to the local source of fine particles.

Generally speaking, the probability cumulative curve of grain size of aeolian sediments in the world is usually shown as 2～4 independent line segments, indicating that 2～4 modes of motion occur during their transportation (Visher, 1964). The probability cumulative curve of grain size of sandy dunes in the Hexi Corridor basically presents a 3-stage pattern, indicating that the sandy dunes here are dominated by the motion mode of saltation under the action of wind, and superimposed with a small amount of particles transported by the motion modes of suspension and creeping. This feature has been observed in sand dunes in different areas of the Hexi Corridor (Zhang and Dong, 2015; Zhang et al., 2016; Pan et al., 2019), including the sand dunes in the lower reaches of the Heihe River Basin near the Hexi Corridor (Zhu et al., 2014). But compared with dune sediments, the movement modes of Gobi sediments and lacustrine sediments are mainly creeping-saltation and saltation-suspension, respectively (Zhu and Yu, 2014; Zhang et al., 2016), indicating that the motion mode of lacustrine sediments and Gobi sediments is different from that of dune sediments. This can also be reflected from the differences in the frequency accumulation curves of dune sediments, Gobi sediments, and lacustrine and fluvial sediments in the Hexi Corridor (Fig. 4). Dune sediments are usually unimodal distribution, while aqueous sediments are usually bimodal or multimodal distribution (Zhu, 2007; Zhu and Yu, 2014).

The above geochemical analysis provides good evidences for the understanding of the material sources of sand dunes in the Hexi Corridor. The factor that sand dunes in the Minqin area have different material sources between the western part (the Badanjilin-Minqin transition zone), the central part, the southeast side, and the eastern part (the Tenggeli-Minqin transition zone) of the Minqin Basin indicate that aeolian sediments from the Badanjilin Desert can be transported to the west side of the Minqin Oasis

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through mountains (Yabulai) for a long distance by the northwest wind, and aeolian sediments from the Tenggeli Desert provide sediment source to the east side of the Minqin Oasis. However, the aeolian sediments of the two deserts cannot reach or bypass the other side of the Oasis (that is, not crossing the oasis barrier to achieve a confluence of the two deserts). This study reveals that the Minqin Oasis is an effective barrier to prevent the migration and convergence of sandy dunes between the Badanjilin and Tenggeli Deserts. However, the large number of aeolian dunes developed in and around the Minqin Basin also suggests that the role of oasis in preventing eaolian erosion is limited and should not be overestimated.

Comparing the major element abundances of aeolian sediments in different deserts of China (Table 3), the barchan dunes in the Hexi Corridor have certain differences and similarities with deserts in northwest and north-central China. For example, the content of Fe_2O_3 in sand dunes of the Hexi Corridor can reach 3.50%, which is generally higher than any one of other deserts, while the contents of other elements in the Hexi Corridor are in a similar range of element abundance to those of other deserts, indicating that the sandy dunes in the Hexi Corridor are rich in iron element. Compared with the composition of the upper continental crust (UCC), dune sediments in the middle and eastern Hexi Corridor are enriched in SiO_2 (Figs. 5-6) and CaO (Fig. 6), which are similar to those in the fluvial and lacustrine sediments near the Taklamakan and Badanjilin Deserts and the aeolian sediments in the surrounding Gobi desert, but they are slightly different from those in the Kumtag and Tenggeli Deserts (Zhang et al., 2020).

The analytical results from heavy mineral assemblages indicate that the provenance of sandy dunes in the Hexi Corridor is mainly from "sands of in-situ rising" (Zhu et al., 1980; Chang, 2019). Researches from palaeogeography believe that sediments from alluvial plains and alluvial deposits of ancient rivers, lacustrine plain and lacustrine deposits of ancient lakes, aeolian deposits in the erosion zone of the southern and northern foothills of the Hexi Corridor, and alluvial deposits of modern rivers are the main material sources of sandy dunes in the Hexi Corridor (MDCES, 1975). Based on mineralogical analysis, Ferrat et al. (2011) observed that sand dunes in the Hexi corridor have similar concentrations of mica, quartz, illite, muscovite and albite with adjacent areas, such as the Tenggeli Desert and the Badanjilin Desert. This similar mineralogical composition may lead to the similarity in geochemical characteristics of aeolian sediments in these areas. Grain-size sedimentological and geochemical studies based on detrital materials suggest that alluvial deposits in the Qilian Mountains, paleo-lacustrine deposits in low-level areas, and surface aeolian deposits in Gobi desert areas are the main material sources for the formation and development of sandy dunes in the Hexi Corridor (Wang and Wang, Zhang and Dong, 2015; Zhang et al., 2016; Zhang et al., 2020).

Summarizing the above characteristics and evidences of sand dunes, it can be concluded that there are two states of dunes in the Hexi Corridor in the past half century, that is, dynamic change and basically stable. This kind of geomorphological evolution is closely related to its material source and regional

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environmental conditions. Dried river deposits (playas), alluvial/proluvial deposits and lacustrine deposits are the main sources of sandy dunes in the Hexi Corridor, while these detrital deposits mainly come from the Qilian Mountains in the south and the Beishan Mountains in the north. Compared with sand dunes in desert areas, sand dunes in the oasis area of the Hexi Corridor have more complex material sources. They are closely linked to regional land degradation and desertification issues in the Hexi Corridor.

4. 2. Mechanisms of land desertification in the Hexi Corridor

Generally speaking, sandy dunes in the Hexi Corridor are dominated by the mobile dunes. In the early research work, the formation of these mobile dunes was considered to be caused by the destruction of vegetation previously fixed on the shrub dunes in the oasis; or because the gravel Gobi desert and related wind-erosion areas in the Hexi Corridor provided abundant sandy sediments, resulting in a wide aeolian-sand transportation and accumulation to form sandy dunes in the corridor area; or because that in the arid Hexi Corridor, the shallow and intermittent rivers with broad riverbeds changed their courses and the abandoned dried riverbeds were blown up by wind, causing accumulation of the fluvial sediments to form sandy dunes near the river banks (Zhu et al., 1980). The mechanisms above-mentioned for the formation of sandy dunes can explain the characteristics of the sporadic or sheet-like distribution of sandy dunes in the Hexi Corridor, especially the characteristics of sandy dunes intermittently distributed along the dried riverbeds by winding and zigzag patterns, and scattered on the gravel Gobi deserts at the edge of oases.

Apart from the above natural causes, it is also believed that the formation of sandy dunes in the Hexi Corridor is not all controlled by the influence of natural factors, some dunes should be formed in historical periods and are the result of human activities (Zhu et al., 1980; Zhu and Chen, 1994; Zhu, 1999; Yang et al., 2004; Chang et al., 2005; Li, 2007). For example, ruins of the Han, Tang, and Ming Dynasties and sites of the Great Wall can also be found in some dune fields, such as the Shouchang ruins in the South Lake area of Dunhuang, the ruins in the dune fields of the Xicheng Post Station to the west of Zhangye, and the sites of the Great Wall of Ming Dynasty in the dune fields in the Minqin area (Zhu et al., 1980; Zhu and Chen, 1994; Zhu, 1999), etc.

Regarding the above desertification mechanisms, the wind-eroded fields in Gobi deserts and its deflation products in the Western Hexi Corridor (the upper windward area) are considered to be one of the reasons for the desertification of the middle and eastern Hexi Corridor, because the former may provide the material basis for the latter to form sandy dunes. However, is the existence of these western Gobi and wind erosion areas really the main cause of desertification in the Hexi Corridor?

In order to solve this problem, researches have been carried out on the Gobi soils, wind-erosion landforms and the intensity and potential of the wind erosion process in the western Hexi Corridor (e.g.,

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Zhu et al., 1980; Zhang et al., 2004; Qu et al., 2005; Wang et al., 2013; Yin et al., 2014, 2016; Zhang et al., 2016; An et al., 2019; Hu et al., 2020). From the perspective of geomorphology, wind-eroded lands are widely distributed in the western part of the Hexi Corridor. The result of surface wind erosion in these areas is the formation of long strip-shaped aeolian monadnocks and deflation hollows (aeolian depressions), which are roughly parallel to the wind direction. Generally, these wind-eroded landforms are about 1～3 meters high, and a few are up to 5 meters (Zhu et al., 1980), which are roughly distributed along the lower reaches of the Shule River and the western part of the Dunhuang Oasis. Studies on the surface properties of gravel desert (Gobi) and its impact on wind erosion and dust emission in the west of the Hexi Corridor have shown that the gravel Gobi is very different from the sandy desert (dune field) because the grain-size composition of the surface sediment and the occurrence state (erodibility) of fine granular material are completely different (Zhang et al., 2004; Yin et al., 2014, 2016; Zhang et al., 2016; Hu et al., 2020). The surface of Gobi desert is composed of the gravel-, sand-, fine-sand- and clay-fraction particles with coarse- and fine-grained materials mixed together, while the surface of dune field is mainly composed of the medium-sand-fraction particles, with no or few coarser-grained gravels and finer-grained silt and clay particles (Zhang et al., 2016; An et al., 2019). A salt crust usually exists on the surface of Gobi desert in the west Hexi Corridor and thus the fine-grained particles are consolidated due to the presence of salt cement, leading to a weak wind erodibility in Godi desert, while the surface of dunes is loose, making a strong erodibility in dune field (Zhang et al., 2016). Because the potential sediment availability (controlled by erodibility of surface fine-grained particles), the gravel coverage (surface roughness) and the average particle size of surface sediments are the main factors affecting dust emission (Pye, 1987; Gillette and Stockton, 1989; Raupach et al., 1993), the three factors will determine whether the Gobi desert in the western Hexi corridor has potential contribution to regional desertification in the Hexi Corridor.

Based on field surveys and using the ImageJ software to process high-resolution image data, Zhang et al. (2016) estimated the gravel coverage and surface salt crust status in different Gobi areas in the west Hexi Corridor, determined the proportion of total surface sediment weight occupied by gravels (diameter > 2 mm), and analyzed the sedimentological grain-size distribution of different land surface sediments. The results of this work show that: (1) in the west Hexi Corridor, the gravel coverage of Gobi surface is moderate, with the gravel coverage mainly between 40% and 70% (average 52%, SD = ± 17%) (Zhang et al., 2016). The rate of gravel coverage in this level can produce the maximum aerodynamic roughness on the ground surface to prevent dust emission (Lyles and Tatarko, 1988; Wolfe and Nickling, 1996; Dong et al., 2002a, 2002b; Liu and Dong, 2003; Uno et al., 2006; Rostagno and Degorgue, 2011). (2) Most of the Gobi surface lands (75% of the total area) have formed salt crust. Only the areas with high sand-transport potential of wind in the northern Hexi Corridor and the edge of sandy deserts have no surface salt crust. (3) The content of erodible materials (sand, silt and clay) on the Gobi surface has a clear spatial distribution.

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Sediments of the Gobi surface are mostly the medium-sand and fine-sand particles (52.5% and 25.0%, respectively), while the silt and clay contents range from 9.8% to 40.1%, with most areas (about 73%) ranging from 10% to 30%. (4) In most Gobi regions, the potential transport of sand material is > 200 vector units, but 75% of these areas have solid soil crust on the ground surface (Zhang et al., 2016).

Combined the above indexes, i.e. the proportion of fine-grained dust materials, the coverage rate of salt crust, and the potential transport of sand material, it is shown that the high level of gravel coverage and surface crust rate in the west Heixi Corridor can effectively reduce the dust emission from the Gobi surface. Therefore, the Gobi area in the west Hexi Corridor is not the main source area of sandstorms occurred in the middle and east of the Hexi Corridor. The northern part of the Hexi Corridor may be the main source area of dust.

Another potential indicator that can indicate the degree of modern desertification in the region comes from the meteorological parameter, such as the number of sandstorm days and strong wind days (Chang et al., 2019). Sandstorm refers to a windy and sandy weather phenomenon with the wind speed ⩾ the sand-blowing wind speed and the horizontal visibility < 1,000 m. The Hexi Corridor is considered to be one of the areas with the most-frequent (heavy) sandstorm in northwest China (Zhu et al., 1994; Zhu, 1999). The results of meteorological data analysis from the Hexi Corridor show that since 1956, the number of local sandstorm days in the Hexi Corridor is about 11.20 day/year (Table 4), and the average number of strong wind days (wind speed >8 grade/day) is about 18.39 days/year (Table 4), but the number of local sandstorm days in the Hexi Corridor has shown a generally-decreasing trend (Fig. 7a), with a decline rate of 0.677 times/year (Chang et al., 2011). In addition, the frequency of sandstorms throughout northern China is also decreasing during the same period (Zhang and Ren, 2003; Li and Zhang, 2007). However, this is contrary to the situation of global sandstorms, because the number of times of global sandstorms is increasing in recent decades (Houghton et al., 2001; Ding, 2002). This indicates that the sandstorm process in the Hexi Corridor and even in the entire northern China does not respond to the global changes, revealing that the cause of desertification in the Hexi Corridor is different from other parts of the world.

As shown in Fig. 7a, the number of sandstorm days in the Minqin area of the Hexi Corridor has shown a decreasing trend as a whole since 1956-2008, and there are three sub-trends during this period, i.e., both the frequency and number of sandstorms decreased rapidly (1956-1969), the frequency was high and stable (1971-1987), and the frequency was low and slowly decreased (1987-2008).

However, with global warming, the temperatures in desert areas are generally increasing (Fig. 7b), and the frequency of sandstorms should have increased, but why has the actual situation reduced?

To answer this question, we need to analyze the climate change in arid northern China and the Hexi Corridor since this period. For nearly half a century, global warming has become a worldwide concern. In

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this context, how does the climate change and respond to global warming in the desert areas of northern China and the Hexi corridor?

Researches on this issue have been carried out in arid regions of northern China and the Hexi Corridor (e.g. Ding, 2002; Sha et al., 2002; Chang et al., 2011, 2016b). Here, we briefly summarize the research results of climate change in the Hexi Corridor (the Minqin arean) in recent decades.

(1) From 1961 to 2008, the rising rate of the annual average temperature in the Minqin area was higher than that of global temperature in the 20th century and that of China in the past 100 years. Among them, the temperature increase in February was the largest, with the monthly average temperature increasing by 3.01 ℃ (Fig. 7b).

(2) From the 1980s to 1990s, the warmest in the world in the 20th century, the extreme maximum temperature in Minqin has increased significantly, while the extreme minimum temperature has decreased intermittently, and the instability of the extreme maximum and minimum temperatures has increased. The detailed results are as follows: the instability of the monthly average temperature in January and April increases; the isothermal date in February is 10.36 days earlier; the instability of the extreme maximum temperature in December and January increases; the variation coefficient of the extreme minimum temperature in May is as high as 287% (Fig. 7C).

(3) During the period 1961-2008, the temperature in the Minqin area increased, the precipitation also shown an increasing trend, and the air humidity also increased significantly (Fig. 7d, 7f).

(4) In the Minqin area, the instability of precipitation increased in January and the stability of annual precipitation increased (Fig. 7e). In general, as with the large-scale regional climate change in northern China, the problem of temperature instability should be more worthy of attention than the problem of temperature warming (Ding, 2002; Sha et al., 2002; Chang et al., 2011, 2016b).

(5) The wind speed in the Minqin area continued to decrease during the period from 1961 to 2008, (Fig. 7g).

(6) There is a significant negative correlation between the annual and seasonal distributions of sandstorms and the relative humidity of air (Fig. 7h).

It can be seen from the above that although the temperature in the Hexi Corridor has increased (in response to global warming), the precipitation has increased (in response to the enhancement of the Asian Summer Monsoon climate), the relative humidity of the air has increased and the wind speed has decreased. As a result of this environmental change, on the one hand, the dynamic force of dust-release process will be reduced (because of the decrease in wind speed), and on the other hand, the viscosity of the surface sediment particles will increase (because of the increase in humidity), which will reduce the frequency of dust storm events. Therefore, since 1961, the decreasing trend of sandstorm days in the Hexi Corridor is mainly due to the increase in the relative humidity of the air, that is, the warming and

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humidification of the local climate is one of the main reasons responsible for the reduction of sandstorms in the Hexi Corridor. In other words, the Hexi Corridor has a potential trend of reverse desertification in the past half century. The main influencing factor of desertification in the Hexi Corridor is climate change, that is, controlled by natural factors.

4. 3. Environmental implications of land desertification in the Hexi Corridor

For more than half a century, in response to the problem of desertification in the Hexi Corridor, local governments and organizations have carried out systematic engineering and theoretical researches on desertification control in the Hexi Corridor. The most significant works and researches have been done on the ecological and geomorphological control of desertification, such as the study on the water physiology and ecology of desert xerophytes, the study of desert climate change and its response to global warming, the study of the phenology of desert plants, and the study of aeolian sediments accumulation on the edge of oasis, etc (Zhu and Wang, 1994; Zhu, 1999). These ecological studies also highlight that the ecological and water environment of the Hexi Corridor has changed greatly with the above-mentioned climatic and geomorphological changes in the Hexi Corridor, such as:

(1) The groundwater level in the Hexi Corridor has fallen and the regional water resources have decreased. For example, the 26 motorized wells located in the inner Minqin Oasis indicate that the groundwater level in the central part of the Minqin Oasis fell at a rate of 0.54m/y during the period 1985-2001 (Fig. 8); and the 7 motorized wells located at the edge of the Minqin Oasis indicates that the groundwater level in the marginal area of the Minqin Oasis also decreased, with a drop rate of 0.56m/y from 1985 to 2017 (Fig. 8).

(2) The area of natural sand-fixing forests in the Hexi Corridor has decreased. Due to the drop of groundwater level, the natural sand-fixing vegetation in the Minqin area has declined on a large scale, and the desert steppe has become sandy field. For example, in 1981, the area of natural sand-fixing forest in the Minqin area was 203,951 hm^2, but by 2002, the area of natural sand-fix forest had decreased to 197,353 hm^2 (Table 5); in the early 1980s, there were 373 hm^2 of Populus euphratica forest in Minqin, but it has now disappeared (Table 5).

The above ecological and hydrological problems tell us that in an arid and desertified environment such as the Hexi Corridor, the reason for the continuous decrease of vegetation is not the lack of afforestation, nor the change of regional precipitation or relative humidity (although the climate in the Hexi Corridor has become more humid in the past half century, as illustrated in Fig. 7), but is subject to the changes of "effective water", such as groundwater and soil water (Fig. 8). In other words, effective moisture is the most restrictive factor for ecological sustainability in the desert environment. Therefore, the control of desertification in an arid environment should be based on the principle of “centering on

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effective water balance". Deviating from the principle of "effective water balance" is a deviation from the basic law of natural environment change in sandy areas. In this contradiction, it is difficult to achieve the control of desertification without the overall direction of water-saving management and research on groundwater.

Therefore, it can be said that the change of water environment is one of the leading factors restricting the change of the ecological environment from an oasis landscape toward a desertified landscape in arid areas. The degradation of the ecological environment in the lower reaches of the Shiyang River Basin in the Hexi Corridor, once again illustrates this point. From a larger spatial scale, the arid and semi-arid areas in northern China are seriously deficient in water resources. How to combat desertification is the primary problem restricting the sustainable development of the region. Some scholars believe that the transfer of water from the outer basins (such as the Yellow River Basin and the Yangtze River Basin) can appropriately alleviate the serious water shortage and desertification in the inland area of the Hexi Corridor. However, is such a measure feasible? In view of the large-scale allocation of resources in arid areas, on the one hand, the transfer of water from the outer basin is not the fundamental solution to the problem, and it is likely to cause ecological problems in other watersheds, because almost every watershed under arid environment is short of water or potentially short of water. On the other hand, large-scale water transfer is also unrealistic. Due to the constraints of socio-economic conditions and financial resources in the Hexi Corridor, it is not feasible to transfer water from the outer basin at least in the near future. We believe that the fundamental way to solve the problem of water resources of the inland areas of the Hexi Corridor lies in the rational utilization of existing water resources. Furthermore, some studies believe that the inland areas of the Hexi Corridor are not an absolute "resource-based water shortage", but a combination of "resource-based water shortage" and "technics-based water shortage" coexist (Chang and Liu, 2003). It means that the utilization of water resources is unreasonable and the efficiency of utilization is not high. Comprehensive control is the only way to combat desertification in the interior of the Hexi Corridor.

5. Conclusion

The formation and dynamic change of sandy dune landforms in the Hexi Corridor is a typical problem of land desertification in the mid-latitudes of Northern Hemisphere, which has attracted great attention from China and the international community for nearly half a century. It is of great significance to study the formation and evolution of aeolian dunes in this area to reveal the process and mechanism of desertification and the related environmental changes. Based on the existing high-resolution satellite image interpretations, field investigations and observations, comprehensive understanding of the evidences from geomorphological, aeolian-physical, granulometrical and geochemical analysis, this study discussed the formation of dune landform, the mechanism of desertification and their environmental

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implications in the Hexi Corridor. The analytical results show that 80% of the sand particles flow within a height of 20~30 cm near the surface, and about half of the sand particles flow within a height of 0.3~0.5 cm near the surface in the Hexi Corridor. The average height of the typical crescent-shaped dunes is about 6.75m, and the minimum and maximum values are between 2.6 and 11.2m. In terms of the inter-annual and multi-year dynamic characteristics of the sandy dunes in the Hexi Corridor, only the crescent-shaped dunes and chains of barchan dunes are moving or wigwagging, while the parabolic and longitudinal dunes did not move. Under the influence of wind speed, strong wind days and other factors, the dunes at the edge of the Minqin Oasis move the fastest, with a moving speed of about 6.2m/a. Affected by the main wind direction and other factors, the dunes at the edge of the Dunhuang Oasis move the slowest, with a moving speed of about 0.8m/a. The main factors affecting the dynamic changes of sandy dunes in the Hexi Corridor are the annual precipitation, the annual average wind speed and the number of annual strong wind days, of which the annual precipitation contributes the largest, indicating that the climate factors have a most important impact on the dynamic change of sand dunes. The cumulative curve of particle size frequency of dune sediments in the Hexi Corridor basically presents a three-segment model, indicating that the dune sediments are mainly in a saltation mode under the action of wind force, superimposed with a small amount of coarser and finer particles dominated by the creeping and suspension models, which is obviously different from that of the Gobi sediments with a dominant two-segment model. The early and recent investigations of dune sources and the sedimentological and geochemical evidences indicate that the sandy dunes in the Hexi Corridor are mainly derived from "locally or in-situ raised sediments", which are mainly come from alluvial plains and ancient fluvial sediments, as well as ancient lake plains and lacustrine deposits in the Hexi Corridor, aeolian deposits in the piedmont denudation zones of the north and south mountains and modern fluvial sediments. In terms of the abundance of major and trace elements, the crescent-shaped dunes in the Hexi Corridor have certain similarities and differences to other sandy dunes in the northwest and northern deserts of China (such as the Kumtag, Badanjilin, Tenggeli, and Taklamakan Deserts, etc.) or aeolian loess in the Loess Plateau. The sandy dunes in the Hexi Corridor are relatively rich in iron and Co. Considering the proportion of fine particles on the surface, the coverage rate of surface salt crust, and the potential migration of erodible sandy materials, it can be concluded that the Gobi in the west of the Hexi Corridor is not the main source area of sandstorms in the middle and east of the corridor, but the north is probably the main source area of dust. In the past half century, the warming and humidification of the local climate is one of the main causes of the reduction of sandstorms in the study area. During the same period, the Hexi Corridor has a potential trend of anti-desertification, which is mainly controlled by climate change, that is, an influence of natural factors. But in the oasis area of the Hexi Corridor, the effective measures to restrict desertification depend on human activities. Comprehensive management and rational utilization of the existing water resources, especially the restriction of the decline of groundwater, is the key to preventing desertification in oases, rather than water transfer from outer river basins.

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Figures and Figure Captions:

Fig. 1 Geographical position of the Hexi Corridor in China

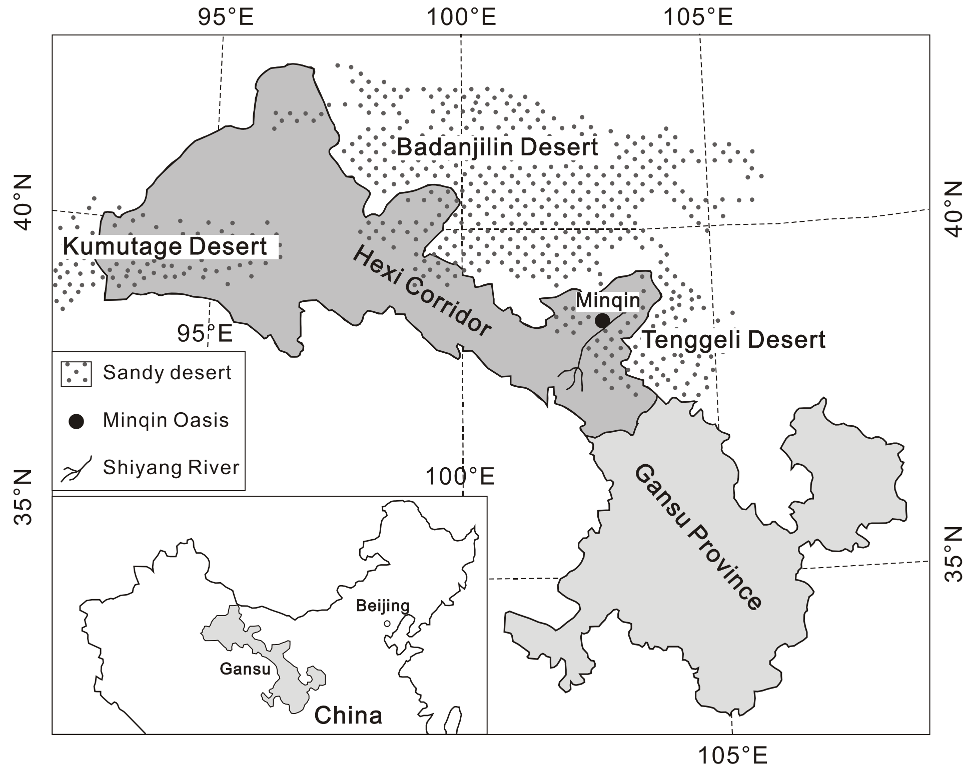

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Fig. 2 Geomorphological map of the Hexi Corridor (modified after Wang, 2003)

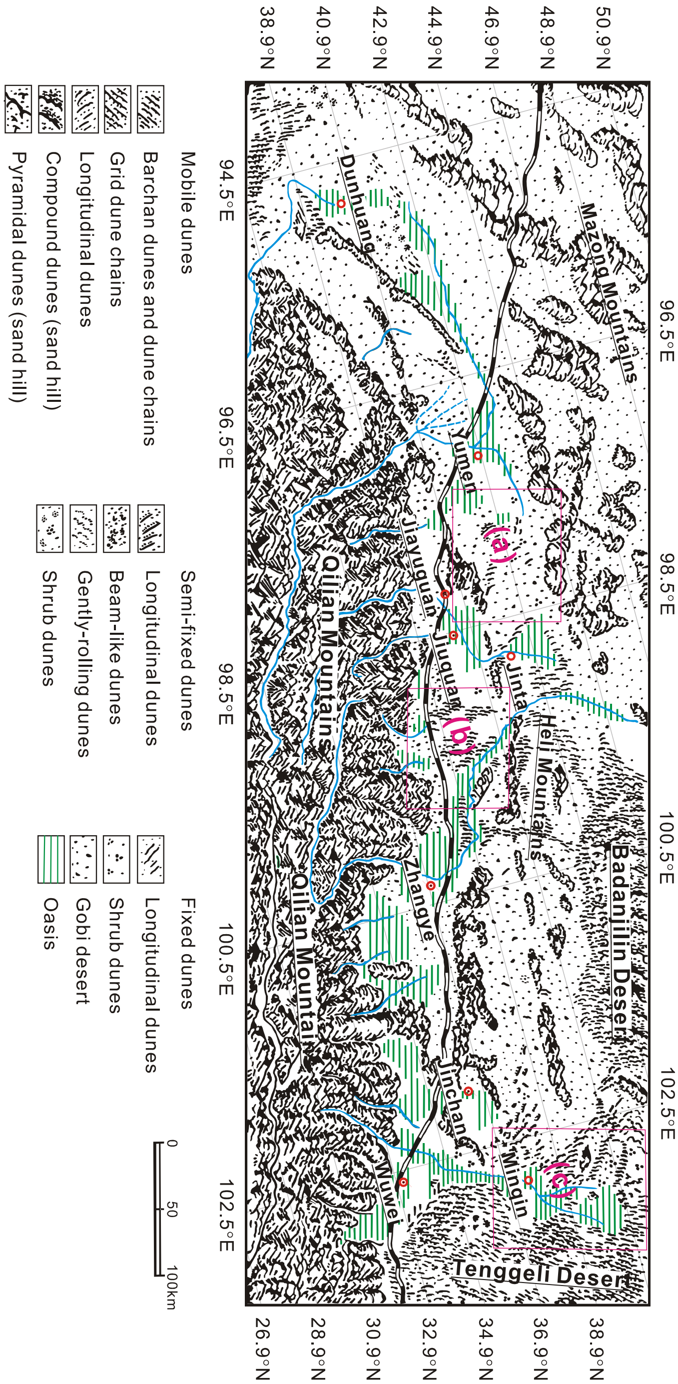

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Fig. 3 The moving speed and height of sandy dunes in the Hexi Corridor (modified after Chang et al., 2016a). (a) the moving speed of crescent-shaped (barchan) dunes (see Table 1 for geographical locations of the corresponding dune IDs); (b) the moving speed of chains of barchan dunes (see Table 1 for geographical locations of the corresponding dune IDs); (c) the moving speed and height of barchans dunes (see Table 1 for geographical locations of the corresponding dune IDs); (d) the moving speed and height of chains of barchan dunes (see Table 1 for geographical locations of the corresponding dune IDs); (e) the movement speed and height of pyramidal dunes (see Table 1 for geographical locations of the corresponding dune IDs).

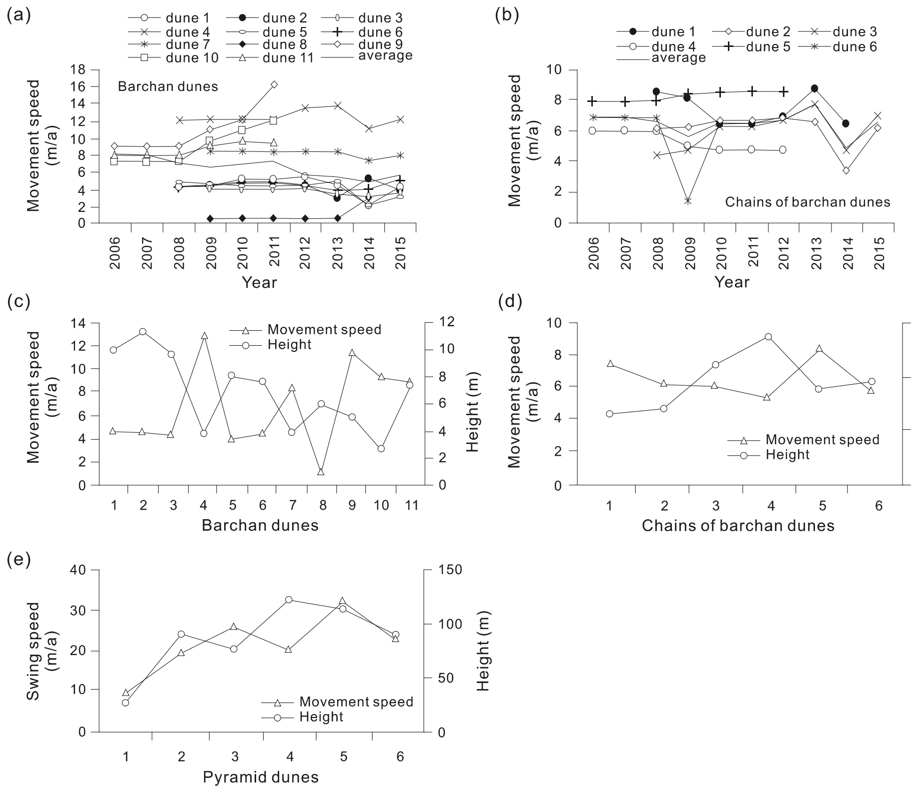

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Fig. 4 The probability cumulative distribution curves of grain size of dune sediments in the Hexi Corridor (modified from Zhang and Dong, 2015)

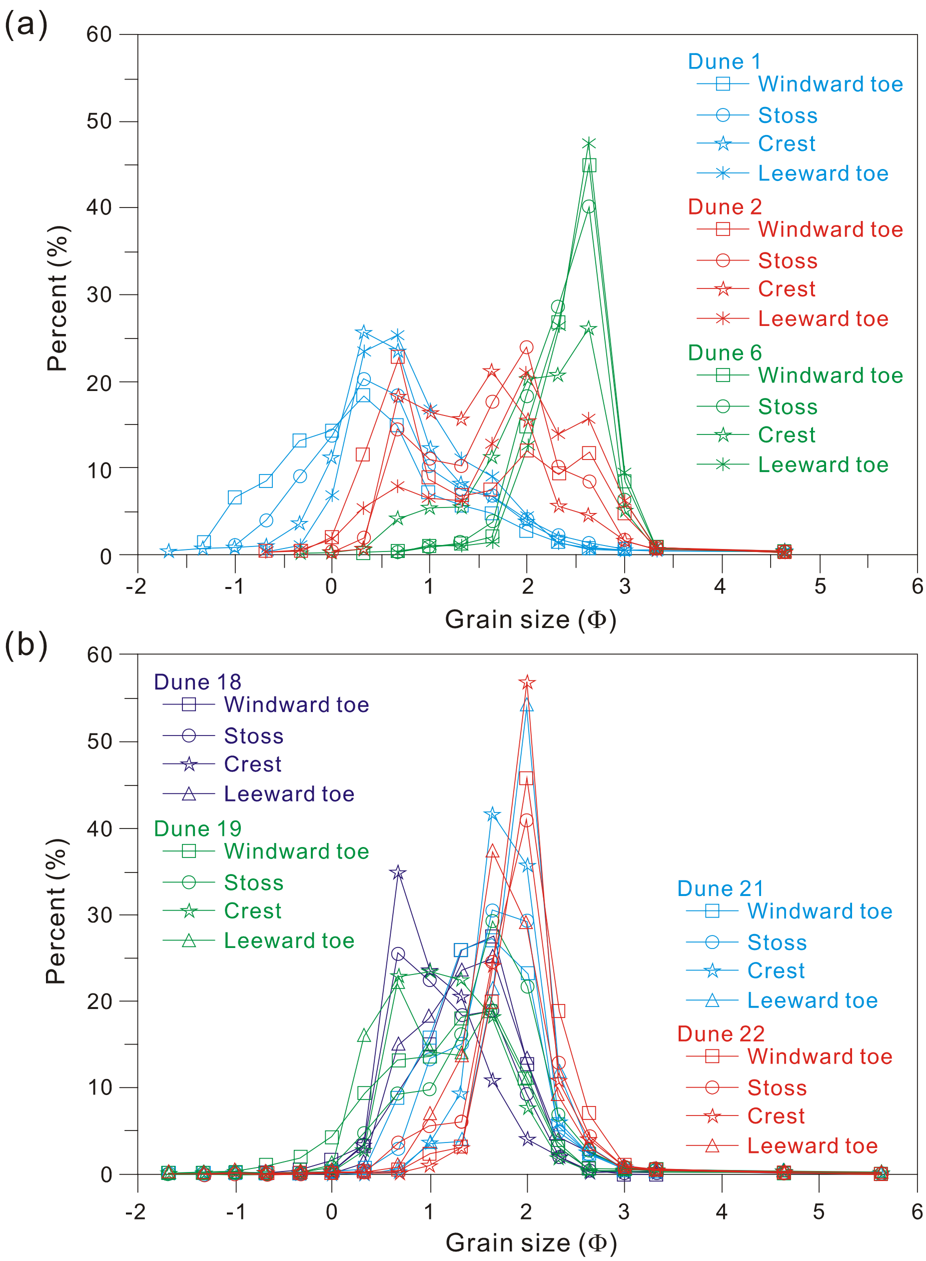

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Fig. 5 The UCC-standardized distributions and compositions of major and trace elements of sand dunes in the Minqin Basin and its surrounding areas in the western Hexi Corridor (modified after Ren et al., 2014)

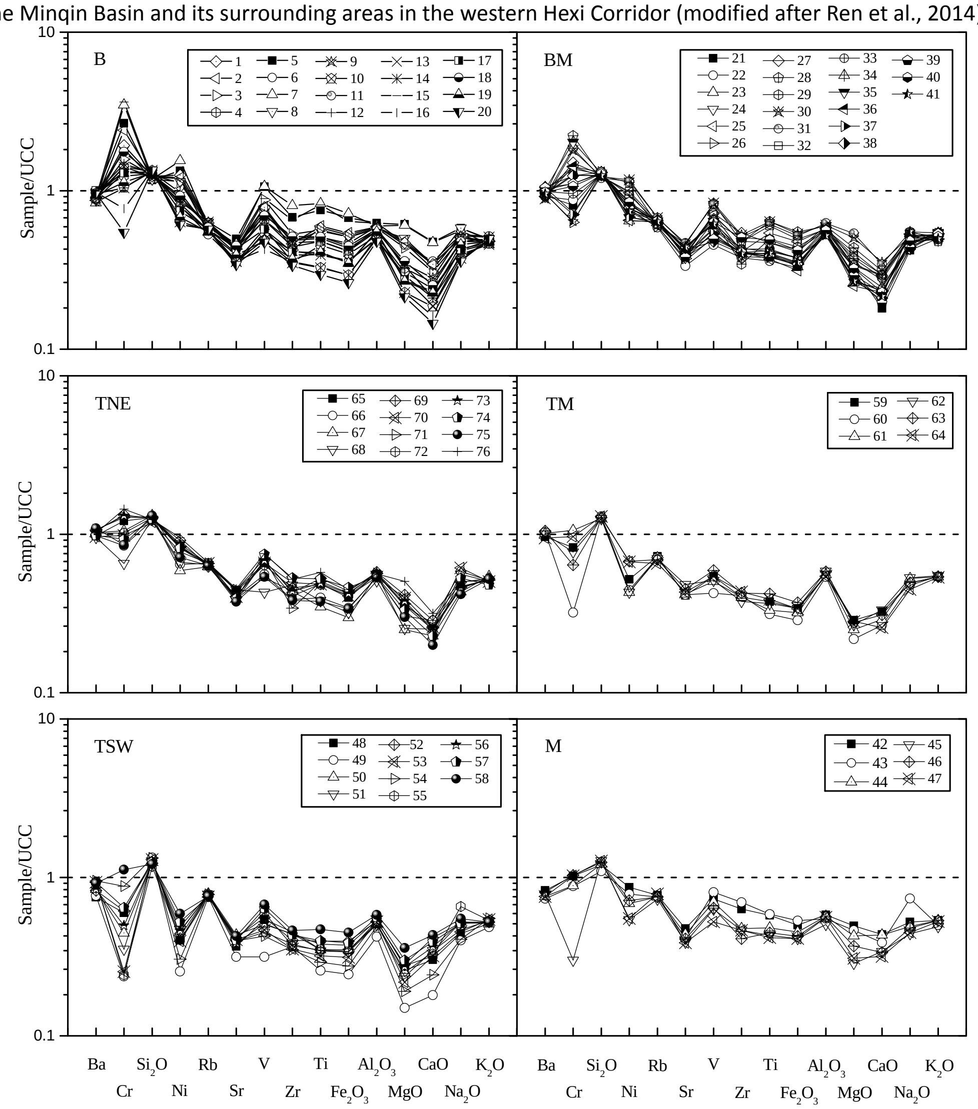

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Fig. 6 Compositions of the major and trace elements and their UCC-standardized distributions of sandy dunes in the Jinta-Gaotai area of the middle Hexi Corridor (modified after Zhang et al., 2020)

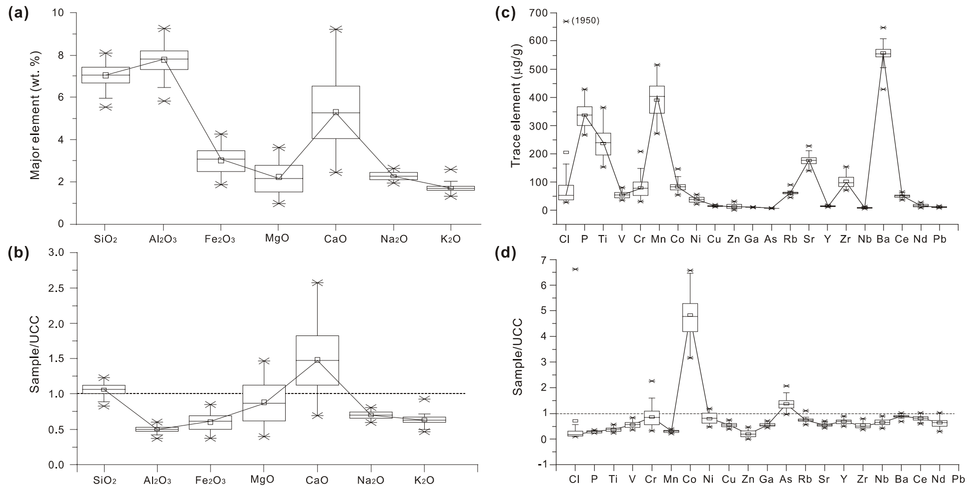

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Fig. 7 Changes of climate parameters in Hexi Corridor in recent 50 years (modified after Chang et al., 2011). (a) Variation of annual average temperature during 1961-2008 in Minqin; (b) Temperature variability during 1961-2008 in Minqin; (c) Variation of annual mean precipitation during 1961-2008 in Minqin; (d) Variation and distribution of precipitation intensity during 1961-2008 in Minqin; (e) Variation of annual relative air humidity during 1961-2008 in Minqin; (f) Variation of annual average wind speed during 1961-2008 in Minqin; (g) Variation of sandstorm days during 1956-2008 in Minqin; (h) Comparison of the monthly average sandstorm days and the monthly average relative air humidity during 1961-2008 in Minqin.

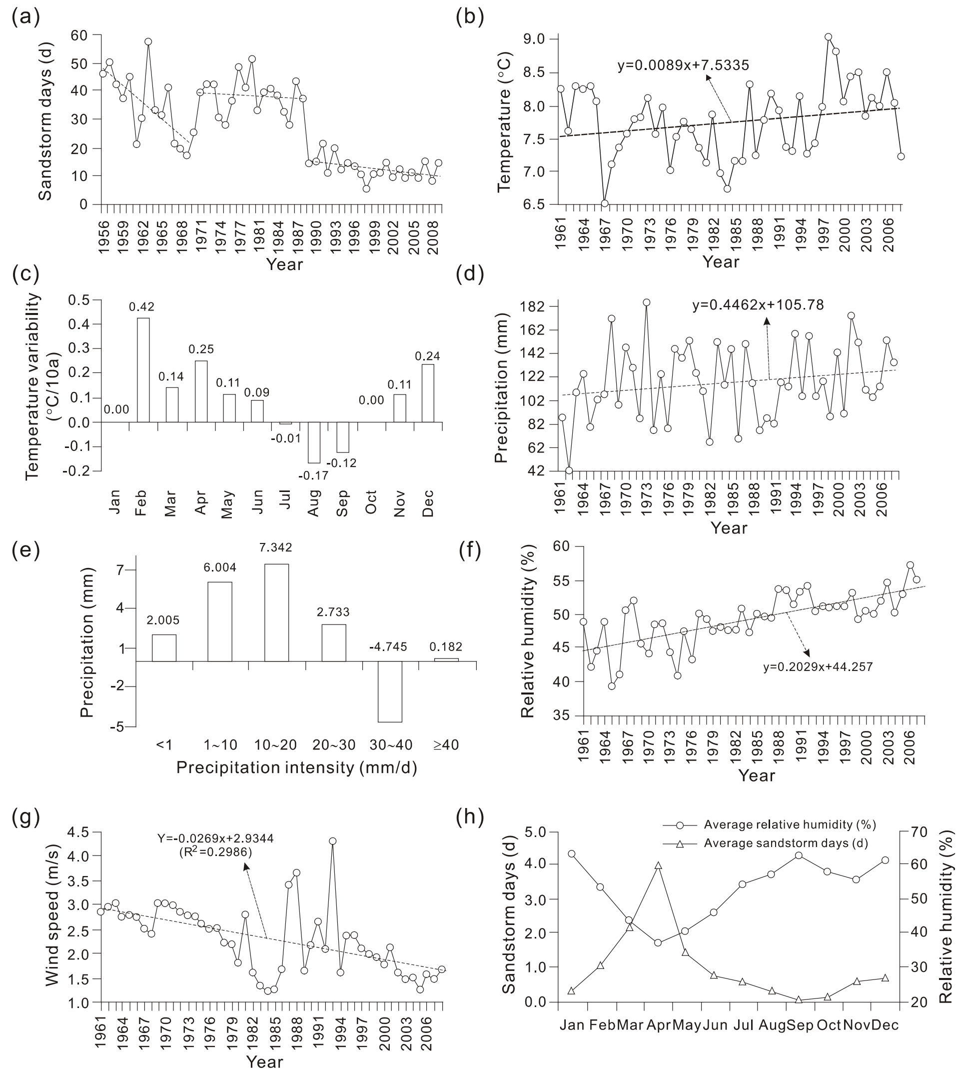

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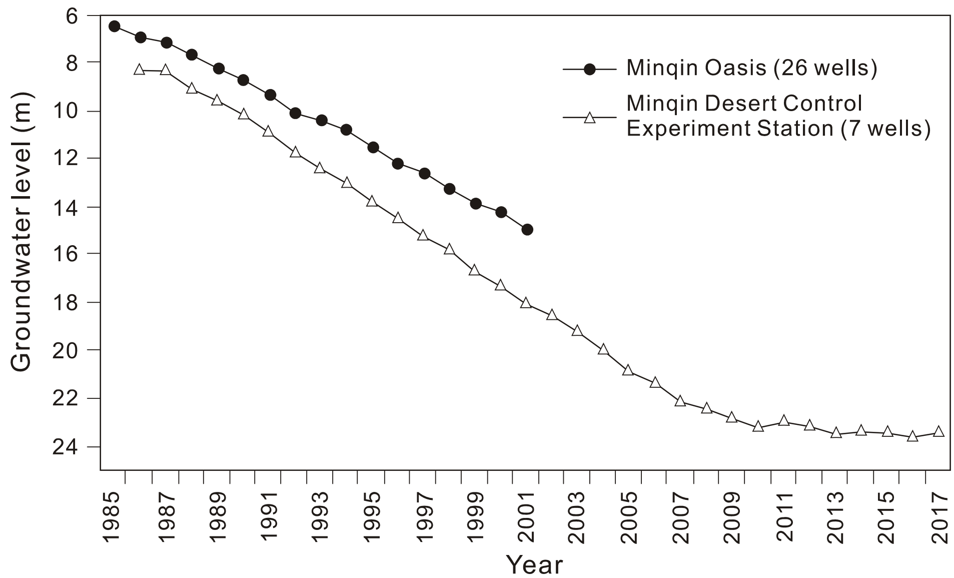
Fig. 8 Variational trend of groundwater levels in the Minqin area (modified after Chang, 2019)



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Tables and Table Captions:

Table 1 the locations, heights, movement directions, and lengths of dunes in the Hexi Corridor

Dune type	Dune ID	Geographic location		Height of dunes (m)	Movement direction (N-W)	Length of the beaches (m)		Source
		Longitude (E)	Latitude (N)			Upwind	Downwind	
Barchan dunes	1	102°55′16′′	38°37′52′′	9.8	48°	438.5	252	Chang et al., 2016a, 2017
	2	102°55′13′′	38°38′00′′	11.2	48	163.3	492.7	Chang et al., 2016a, 2017
	3	102°55′05′′	38°36′06′′	9.5	48°	129.2	163.3	Chang et al., 2016a, 2017
	4	102°55′02′′	38°37′51′′	3.7	48°	304.2	484.1	Chang et al., 2016a, 2017
	5	102°56′34′′	38°32′11′′	7.9	45°	271.7	229.4	Chang et al., 2016a, 2017
	6	102°56′43′′	38°31′59′′	7.6	46°	762.3	430.1	Chang et al., 2016a, 2017
	7	102°54′37′′	38°25′47′′	3.9	45°	295.9	80.8	Chang et al., 2016a, 2017
	8	102°52′56′′	38°25′17′′	5.9	87°	42.6	52	Chang et al., 2016a, 2017
	9	98°49′44′′	39°57′41′′	5	51°	350.4	254.5	Chang et al., 2016a, 2017
	10	98°49′59′′	39°58′07′′	2.6	54°	222.8	437.9	Chang et al., 2016a, 2017
	11	98°49′18′′	40°00′41′′	7.2	57°	184.6	197.3	Chang et al., 2016a, 2017
Chains of barchans dunes	12	102°54′53′′	38°37′46′′	6.4	54°	726.9	752.8	Chang et al., 2016a, 2017
	13	102°55′55′′	38°37′48′′	5.8	54°	443.4	406.7	Chang et al., 2016a, 2017
	14	102°54′46′′	38°37′24′′	11.1	50°	794.8	658.4	Chang et al., 2016a, 2017
	15	98°51′17′′	39°57′59′′	13.8	53°	413.6	361.1	Chang et al., 2016a, 2017
	16	98°51′31′′	39°57′31′′	8.7	54°	501.8	466.2	Chang et al., 2016a, 2017
	17	98°48′04′′	39°58′50′′	9.6	53°	554	445	Chang et al., 2016a, 2017
Pyramid dunes	18	94°42′23′′	40°05′16′′	25.8	SW-NE	/	/	Chang et al., 2016a, 2017
	19	94°42′10′′	40°05′14′′	90.3	SW-NE	/	/	Chang et al., 2016a, 2017
	20	94°41′47′′	40°05′11′′	76.6	SW-NE	/	/	Chang et al., 2016a, 2017
	21	94°40′53′′	40°05′11′′	121.8	SW-NE	/	/	Chang et al., 2016a, 2017

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	22	94°40′43′′	40°05′09′′	114.1	SW-NE	/	/	Chang et al., 2016a, 2017
	23	94°40′12′′	40°05′24′′	88.9	SW-NE	/	/	Chang et al., 2016a, 2017
Parabolic dunes	24	102°57′15′′	38°36′27′′	4.6	/	286.1	35.3	Chang et al., 2016a, 2017
	25	102°57′42′′	38°36′26′′	4.4	/	228.9	188	Chang et al., 2016a, 2017
	26	102°58′15′′	38°36′10′′	3.3	/	133.3	198.5	Chang et al., 2016a, 2017
	27	93°59′40′′	38°37′08′′	3.7	/	396	302.2	Chang et al., 2016a, 2017
	28	98°41′36′′	41°35′64′′	4.4	/	59.9	0	Chang et al., 2016a, 2017
	29	98°41′20′′	40°08′51′′	4.1	/	15.7	17.7	Chang et al., 2016a, 2017
Accumulated sand-belts (longitudinal dunes belts)	30	103°12′36′′	38°47′57′′	15.2	/	70.4	farmland	Chang et al., 2016a, 2017
	31	103°13′30′′	38°48′36′′	17.1	/	44	farmland	Chang et al., 2016a, 2017
	32	103°32′03′′	39°02′12′′	18.6	/	811.7	farmland	Chang et al., 2016a, 2017
	33	103°31′29′′	39°02′10′′	5.6	/	707.7	farmland	Chang et al., 2016a, 2017
	34	103.29′49′′	39°02′34′′	12.2	/	1557.6	farmland	Chang et al., 2016a, 2017
	35	103°26′19′′	39°02′20′′	9.4	/	207.1	223.4	Chang et al., 2016a, 2017

1135
1136 Table 2 Morphological characteristics of barchans dunes in the Hexi Corridor

Dune ID	Plots area	Height (m)	Thickness of camponotus (m)	Length (m)	Width (m)	Slope of leeward direction (°)	Forward direction (°)	Beach land length of upwind (m)	Beach land length of downwind (m)	Source
1	Minqin 3-1	9.8	123.3	214.6	202.5	32.6	N48°W	662.9	378	Chang et al., 2017
2	Minqin 3-2	11.2	155.7	294.4	227.4	32.2	N48°W	163.3	491.6	Chang et al., 2017
3	Minqin 3-3	9.5	12.5	197.5	209.8	32.1	N48°W	134.2	176.6	Chang et al., 2017
4	Minqin L	3.7	78.8	86.5	81.8	31.8	N48°W	251.8	367.8	Chang et al., 2017
5	Minqin 9	7.9	90.8	112.5	81.5	32.9	N45°W	214.3	253.3	Chang et al., 2017
6	Minqin 10	7.6	86.7	136.8	64.7	31.5	N46°W	137.9	430.1	Chang et al., 2017

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7	Minqin 11	11.6	104.4	183.6	57.3	31.6	N46°W	179.9	243.1	Chang et al., 2017
8	Minqin 12	8.6	64.1	131.4	77.9	30.1	N46°W	135.2	697.3	Chang et al., 2017
9	Jinchang 1	8.4	130.3	197.6	123.2	31.7	N55°W	227.4	372.1	Chang et al., 2017
10	Jingta 1	6	83.7	125.3	104.8	31.5	N63°W	250.4	129.5	Chang et al., 2017
11	Jinta 2	5.3	73.5	104.8	76.6	31.7	N63°W	108.2	419.8	Chang et al., 2017

Table 3 The average element contents (%) of sandy dunes in the Hexi Corridor and other deserts and the average composition of the upper continental crust (UCC). CLP, the Loess Plateau in China.

Regions	Fe2O3	CaO	MgO	SiO2	Al2O3	Na2O	K2O	References
Hexi Corridor	3.5	5.55	2.07	66.12	9.24	2.45	2	Zhang et al., 2017; Pan et al., 2019
Badanjilin Desert	1.93	2.06	1.19	80.27	7.78	1.9	2	Zhu and Yang, 2009
Tenggeli Desert	1.96	1.3	1.12	80.94	8026	1.88	2.25	Zhu and Yang, 2009
Kumutage Desert	2.88	4.64	2.19	70.13	9.59	2.52	1.98	Dong et al., 2011
Taklamakan Desert	3.1	7.88	2.2	62.05	10.6	2.58	2.11	Zhu and Yang, 2009
Loess (CLP)	4.56	8.62	2.31	58.65	11.86	1.68	2.44	Dong et al., 2011
paleosol (CLP)	5.12	0.83	2.21	65.18	14.79	1.41	3.15	Dong et al., 2011
UCC	5	4.2	2.22	66	15.2	3.9	3.4	Taylor and McLennan, 1985
Terrestrial shale	7.22	1.3	1.2	62.8	18.9	1.2	3.7	Taylor and McLennan, 1985

Table 4 Meteorological data of sandstorm and strong wind in the Hexi Corridor (cited from Chang et al., 2015)

Weahter Station	Average wind speed (m/s)	Wind speed ≥ 8 grade/d	Sandstorm days (d)	Maximum wind direction
Gulang	3.5	4.5	4	NW
Wuwei	1.8	9.7	4.8	NW
Minqin	2.7	25.1	27.4	NW
Jinchang	3.3	25.1	27.4	NW
Yongchang	3	24.6	4.2	NW
Zhangye	2	12.2	11.8	NNW

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Linze	2.5	21.7	7.7	NW
Gaotai	2	7.8	11.1	NW
Jiuquan	2.2	16.6	10.3	NNW
Jinta	1.9	14.4	6.4	NW, WNW
Yunmen	3.8	40.6	8.1	WNW
Average	2.61	18.39	11.2	/

Table 5 Changes in the area of the sand-fixing forest in different years in the Minqin Basin (cited from Chang, 2019)

Year	Planted forest								Natural forest					
	Arbor forest		Shrub forest						Nitraria tangutorum earth bags with different coverages			Chinese Tamarisk earth bags	Korshinsk Peashrub	euphrates poplar
	Elaeagnus angustifolia	other	Haloxylon ammodendron	Hedysarum scoparium	Korshinsk Peashrub	Salix glabra	Chinese Tamarisk	other	≥ 0.4	< 0.3	< 0.1			
1981	16840	855.9	13044	171.8	19	690.9	227.7	4	23379	36377	12662	5238	125922	372.6
2002	16700	/	44600	100	3508	/	/	132800	19560	19560	14860	5011	125922	0