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Grain-size Characteristics of Sediments Formed Since 8600 yr B.P. in Middle Reaches of Yarlung Zangbo River in Tibet and Their Paleoenvironmental Significance

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Abstract: Widespread aeolian sediments have been found in the middle reaches of the Yarlung Zangbo River, China. The grain-size characteristics of sediments from Cha'er Section in the area were analyzed. The results show that the section include one stratum of paleo-mobile dunes, four strata of paleo-semi-fixed dunes, two strata of paleo-fixed dunes, one stratum of sandy immature soils. The paleo-mobile and paleo-semi-fixed dune sand in this section are similar to modern aeolian sand in either grain-size composition or Mz and σ distribution. Compared the above types of dunes each other, the content of sand substance decreases, while the content of silt and clay increases for paleo-fixed dunes and sandy immature soils. Combined with age data for each stratum, the analysis shows that these strata are the products of climate changes and the evolution of aeolian landforms. The evolutionary sequence of the paleoclimate and of aeolian activities in the valley since 8600 yr B.P. reveals four stages: 8600–5700 yr B.P., when the paleoclimate was cold and dry, with strong winds, thereby activating dunes; 5700–3600 yr B.P., when it was warm and wet, with weak winds, causing dunes to undergo soil-forming processes; 3600–1900 yr B.P., when climate shifted from cold-dry with strong winds to warm-wet with weak winds, and activated dunes were fixed again; and 1900 yr B.P. –present, when the climate became fine, with weak winds, fixing dunes again.

Keywords: Holocene; Tibet; Yarlung Zangbo River; grain size characteristics; Cha'er Section

1 Introduction

Aeolian sediments, especially aeolian sands carry considerable information about global changes at the time of their deposition. Considerable researches have been done on the aeolian sediments, and the results show that the arid and semi-arid areas in Northwest China and the Qinghai-Tibet Plateau experienced several times of aeolian activities during the Holocene (Gao et al., 1993; Dong et al., 1993; Li et al., 1995; Jin et al., 2001). Modern aeolian sandy landforms and quaternary aeolian sediments are widespread throughout the middle reaches of the Yarlung Zangbo River (Liu et al., 1997; Jin et al., 1998; Li et al., 1999; Chang et al., 2006), which are the main sediments to study environmental changes of this area since the Quaternary. Jin et al. (1996; 1998; 2000) thought that southwest monsoon in the middle Qinghai-Tibet Plateau experienced several times of prosperity and decline and regional environment experienced several fluctuations between warm-wet and cool-dry climates. With the optically stimulated luminescence (OSL) dating, geochemical, mineralogical, and granulometric evidences of loess, Sun et al. (2007) considered that the loess in the southern Tibet has a glacial origin, resulting from eolian sorting of glaciofluvial outwash deposits from braided river channels or alluvial fans by local near-surface winds. Current researches provide an important perspective for us to comprehend the environment changes and their causes in the middle reaches of the Yarlung Zangbo River. These researches mainly focus on aeolian loess over long time series (Jin et al., 1996; 1998; 2000; Sun et al., 2007), and few are on aeolian sandy sediments in the middle

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reaches of the Yarlung Zangbo River since the Holocene, which make it necessary to ascertain the content and form of sediments in this period and their relationship with environmental changes. Obviously, the research in aeolian activities and paleoenvironment evolution in this region since the Holocene has very important meaning in the theory and application of desertification combating. In this paper, we discuss the grain-size characteristics of these sediments formed since 8600 yr B.P. in the middle reaches of the Yarlung Zangbo River and their paleoenvironmental significance.

2 Methods

2.1 Description of Cha'er Section

The wide valley along the middle reaches of the Yarlung Zangbo River is located in the southern Qinghai-Tibet Plateau, China, which is currently experiencing a semi-arid temperate monsoon climate. Precipitation varies greatly all year around, with distinct dry and wet seasons (CSEQXP-CAS, 1988). Most of precipitation comes in summer due to the influence of a southwest monsoon, and it is cold and windy in winter because of the westerly jet stream. Cha'er Section (29°23′22″N, 89°16′56″E, 3856m a.s.l.) is located on the terrace (an average height of about 30m above the river level) of the north bank of the Yarlung Zangbo River, 5km west of Cha'er Town of Namling County, Tibet Autonomous Region (Fig. 1). It is mainly composed of interbedded aeolian sands and paleosols, whose thickness is 3.68m, and includes eight strata (Fig. 1).

Stratum 1 is paleo-fixed dune sands, mainly dark greyish-yellow medium fine sands with some finer sands, compact, poor sorted, root tissues and tree bark can be seen, and thickness is 8cm.

Stratum 2 is paleo-semi-fixed dune sands, mainly dark greyish-yellow medium fine sands, loosening, well sorted, with root tissues at the upside, and thickness is 32cm.

Stratum 3 is paleo-fixed dune sands, mainly greyish-yellow medium fine sands with some finer sands, compact, poor sorted, root tissues can be seen, and thickness is 52cm.

Stratum 4 is paleo-semi-fixed dune sands, mainly greyish-yellow medium fine sands, loosening, well sorted, and thickness is 56cm.

Stratum 5 is sandy immature soils, light drab fine sands, compact, slightly cementing, poor sorted, root tissues can be seen, and thickness is 94cm.

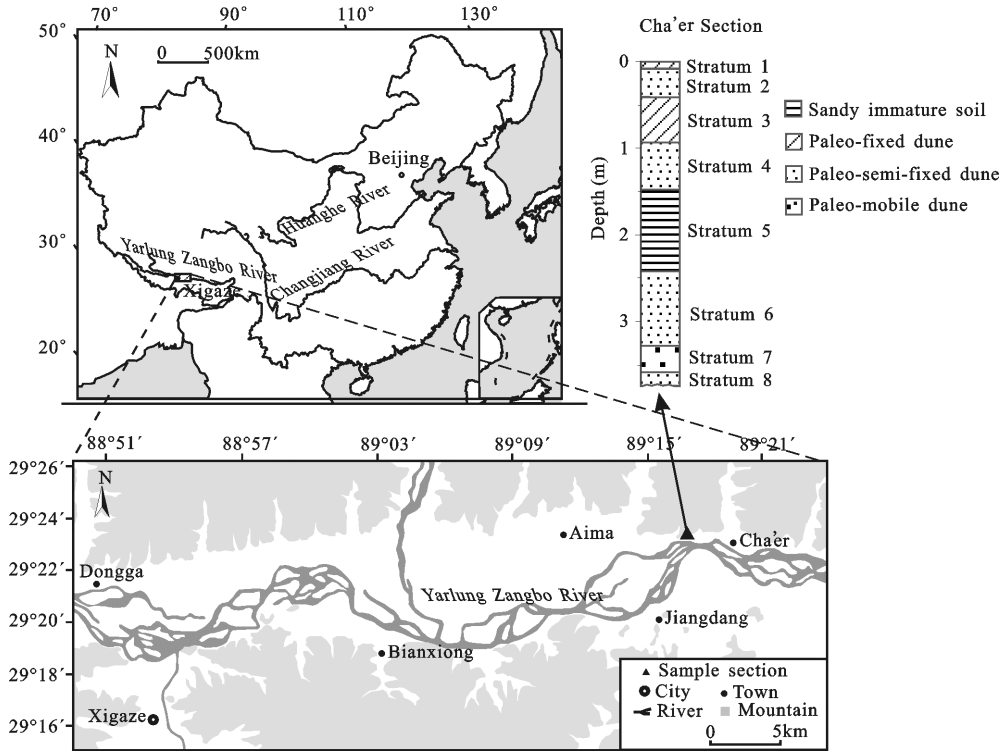


Fig. 1 Location of sample section

Stratum 6 is paleo-semi-fixed dune sands, mainly light yellow medium fine sands, loosening, well sorted, root tissues can occasionally be seen, and thickness is 86cm.

Stratum 7 is paleo-mobile dune sands, mainly light grayish-yellow medium fine sands, loosening, well sorted, and thickness is 30cm.

Stratum 8 is paleo-semi-fixed dune sands, mainly light yellow medium to fine sands, loosening, well sorted, and thickness is 10cm.

2.2 Sample collection and analysis

We collected three samples for ^{14}C dating of Cha'er Section, at depths of 60–70cm, 160–170cm, and 230–240 cm. ^{14}C dates were determined at the Institute of Geology, China Earthquake Administration. And we collected one sample for thermoluminescence (TL) dating at a depth of 350–360cm, and performed the analysis at the State Key Laboratory of Loess and Quaternary Geology.

We also collected 184 sediment samples at 2-cm intervals for grain-size analysis from the top to the bottom of the eight strata of Cha'er Section. The grain-size analysis was conducted at the Key Laboratory of Environmental Change and Natural Disaster, Beijing Normal University. Samples were pretreated as follows: 1) We air-dried 0.5–3.0g of sand (passed through a 2-mm sieve), weighed the sample, and added 10mL of 10% hydrogen peroxide (H_2O_2) solution to get rid of organic matter. We then heated the mixture on an electric hot plate until the H_2O_2 had reacted completely. 2) We then washed the beaker containing residues with distilled, de-ionized water, added 3mL of 10% hydrochloric acid (HCl) to get rid of carbonates, and then heated the mixture until it boiled. 3) We washed the residues with distilled, de-ionized water, and then filled the beaker with water and left the mixture over night. We repeated this process two to three times for each sample. 4) Just before measurement, we added 10mL of $(NaPO_3)_6$ and rested the mixture for 15 minutes (Lu and An, 1997a; 1997b).

The samples were then analyzed with a Laser Particle Sizer (Mastersizer 2000, Malvern Company, Malvern UK), which is capable of measuring particles ranging in size from 0.02μm to 2000μm, with a ±5% measurement error. The classification standards for the samples obtained from this section were based on the general classification principles as follows: 2.0–0.5mm sand is coarse, 0.50–0.25mm one medium, 0.25–0.05mm one represents fine, 0.05–0.005mm one silt, and <0.005mm one clay.

2.3 Calculation of grain-size parameters

In this paper, the mean grain size (Mz) and the sorting index (σ, the standard deviation) are selected as main indexes for discussing the depositional environment evolution of the aeolian sediment in Cha'er Section. We calculated Mz and σ for each sample using the equations (1) and (2) (Folk, 1966):

$$Mz = (\Phi_{16} + \Phi_{50} + \Phi_{84}) / 3 \quad (1)$$

$$\sigma = [(\Phi_{84}-\Phi_{16}) / 4] + [(\Phi_{95}-\Phi_{5}) / 6.6] \quad (2)$$

where Φ_5, Φ_{16}, Φ_{50}, Φ_{84} and Φ_{95} are the grain-size when the cumulative percentage reach 5%, 16%, 50%, 84% and 95%. For convenience, we have expressed the grain-size by its logarithm using the following transformation Equation (3) (Wu, 1987):

$$\Phi = -\log_2 d \quad (3)$$

where d is the grain diameter (mm).

3 Results

3.1 Ages of Cha'er Section

The ^{14}C dating results of the 3 samples from top to bottom of Cha'er Section are 2210±90 yr B.P., 3350±110 yr B.P., 4990±120 yr B.P., respectively, and calibrated by CALIB software of version 5.0.1 (http://calib.qub.ac.uk/), and the calibrated results are 2233±101 cal yr B.P., 3578±128 cal yr B.P., and 5692±84 cal yr B.P., respectively. And the thermoluminescence dating result of the sample collected from bottom of this section is 8560±650 a B.P. Combined with the age data from the ^{14}C and TL analyses, we estimate the ages of the different strata by the average sedimentary ratios calculated separately through the sediment thichness between two ages (Table 1).

Table 1 Ages of Cha'er Section

Stratum	Depth (cm)	Dating result (yr B.P.)	Calendar age (yr B.P.)	Stratigraphical age (yr B.P.)
1	0–8			0–1490
2	8–40			1490–1900
3	40–92	Middle 2210±90 ^{14}C	2233±101	1900–2570
4	92–148			2570–3580
5	148–242	Top 3350±110 ^{14}C	3578±128	3580–5700
		Bottom 4990±120 ^{14}C	5692±84	
6	242–328			5700–7960
7	328–358			7960–8560
8	358–368	8560±650 TL		8560–

Notes: For ^{14}C, we assumed a half-life of 5568 years, and a start date of 1950 AD

3.2 Grain-size distribution

Grain-size analysis shows that sediments from Cha'er

Section consists mainly of sand, which averages 86.64% by mass, and is composed mainly of medium and fine sands, whose corresponding average contents are 32.19% and 46.64% by mass. The average content is 7.81% for coarse sand, 10.61% for silt and 2.75% for clay.

Based on the results of the grain-size analysis, the cumulative grain-size distribution (percent of total mass) for the different strata in this section is shown in Fig. 2. The sediments in Stratum 7 are composed almost entirely of sand (mainly medium and fine sands). The sand content of 97.08% is similar to that of the modern mobile sand dunes in this region and surrounding areas, which averages 98.81% (Liu et al., 1997). The silt and clay contents in this stratum are lower than those in all other strata. Because of the similarity between these sediments and those of modern mobile sand dunes in this region, this stratum can be classified as paleo-mobile sand dunes.

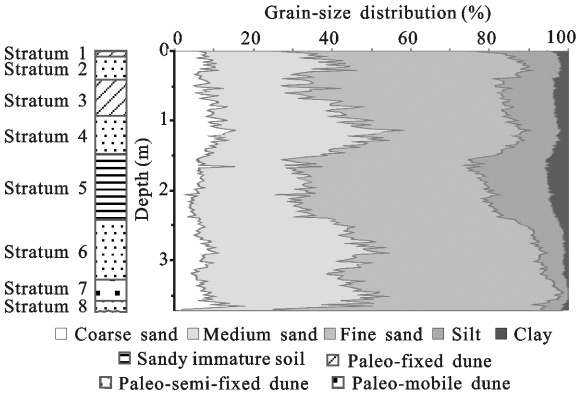


Fig. 2 Cumulative grain-size contents in various strata of Cha'er Section

The grain size compositions in the strata 2, 4, 6, and 8 are similar to each other. The sand contents (85% to 95% by mass) in those strata are similar to that of modern semi-fixed dunes (i.e., 94%). The sandy components of those strata are mainly comprised of medium and fine sands, with the contents of medium sand amounting for 29.81%, 36.12%, 37.79%, and 30.96% of the total, respectively, and fine sand 50.11%, 39.50%, 47.03%, and 53.76%, respectively. The silt and clay contents are higher than those in the Stratum 7, and the content of coarse sand is higher than that in the surrounding strata. Because the grain-size compositions in the strata 2, 4, 6, and 8 are similar to those of modern semi-fixed dunes, these four strata represent paleo-semi-fixed dunes.

The strata 1 and 3 are characterized by medium and fine sands, with the contents of medium sand amounting for 24.43% and 27.74%, respectively, and fine sands 49.25% and 47.05%, respectively. But the silt and clay contents in those strata are higher than those in the strata 2, 4, 6, and 8. On this basis, the strata 1 and 3 represent paleo-fixed dunes. Fine sand is the main component in Stratum 5, with a content of 46.63%. The silt and clay contents in this stratum are 16.15% and 4.66%, respectively, which are higher than those in the other strata. On this basis, it can represent sandy immature soils, and has experienced a soil-forming process.

3.3 Grain-size parameters

According to equations (1) and (2), the mean grain size (Mz) and the sorting index (σ, the standard deviation) were calculated (Table 2 and Fig. 3), which reflect the phase of each sample in different strata.

Table 2 Grain-size parameters for modern aeolian sands and eight strata of Cha'er Section

	Mz (Φ)		σ	
	Average	Range	Average	Range
Modern aeolian sand	2.07	1.60–2.90	0.60	0.40–0.91
Whole Cha'er section	2.55	1.94–3.32	1.49	0.79–2.17
Stratum 1	2.91	2.69–3.24	1.72	1.61–1.87
Stratum 2	2.56	2.30–2.79	1.45	1.30–1.56
Stratum 3	2.71	2.40–2.96	1.71	1.67–1.80
Stratum 4	2.42	1.98–2.68	1.62	1.36–1.78
Stratum 5	2.97	2.67–3.32	1.86	1.54–2.17
Stratum 6	2.24	1.97–2.53	1.15	0.97–1.50
Stratum 7	2.10	1.94–2.21	0.87	0.79–0.92
Stratum 8	2.28	2.05–2.58	1.11	0.99–1.27

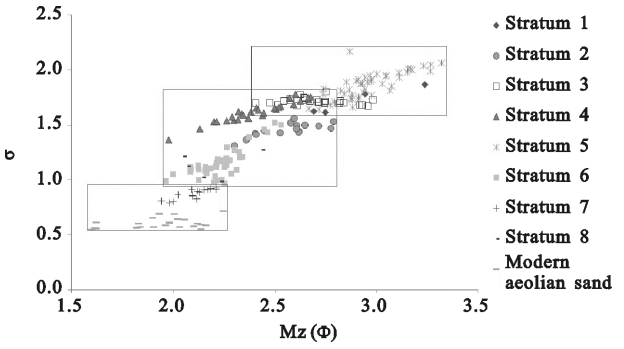


Fig. 3 Mz versus σ scatterplot for eight strata of Cha'er Section

The ranges of Mz values in the strata 2, 4, 6, 7, and 8 are similar to that in modern aeolian sands in the region and its surroundings. The range of Mz values in Stratum 7 is closer to that of modern aeolian sands than those in other strata, which means that the sediments in this stratum is the paleo-accumulation similar to modern

aeolian sand. The ranges of Mz in strata 1 and 3 are similar to that of modern dune sands, but the average values are considerably finer than that of modern aeolian sands, which suggests that the carrying force experienced by the sediments of these strata was weaker than that experienced by modern aeolian sands. The mean values of Mz in Stratum 5 are obvious finer and the range of Mz is different from that of modern aeolian sands, which indicates that the carrying forces experienced by these sediments were weaker.

The mean and range of σ in Stratum 7 are closest to those of modern aeolian sands, and the average value of σ is lower than those of other strata in the Cha'er Section, indicating better sorting in this stratum. The mean values of σ in strata 1, 3 and 5 are clearly much higher than that in modern aeolian sands. This indicates worse sorting and a stronger intensity of weathering and soil formation in those three strata, especially in Stratum 5.

Different depositional environments can be distinguished in a scatter plot of Mz versus σ (Fig. 3) (North Shaanxi Team of Chengdu College of Geology, 1976). Figure 3 shows that data of Stratum 7 are close to those of modern aeolian sands, reflecting a similar depositional environment. Data of strata 2, 4, 6 and 8 are relatively centralized, reflecting a similar depositional environment within those strata. Data of strata 1, 3 and 5 are centralized despite of some overlaps with the values of strata 2 and 4, and the grain-size characteristics of those strata differ from those of the other strata. Therefore, we can infer that depositional environments of strata 1, 3 and 5 are similar but different from those of other strata. Furthermore, the transitional characteristics of the data distribution show that the depositional environments of strata 2, 4, 6 and 8 are the transitions among the depositional environments of Stratum 7 and of strata 1, 3, and 5.

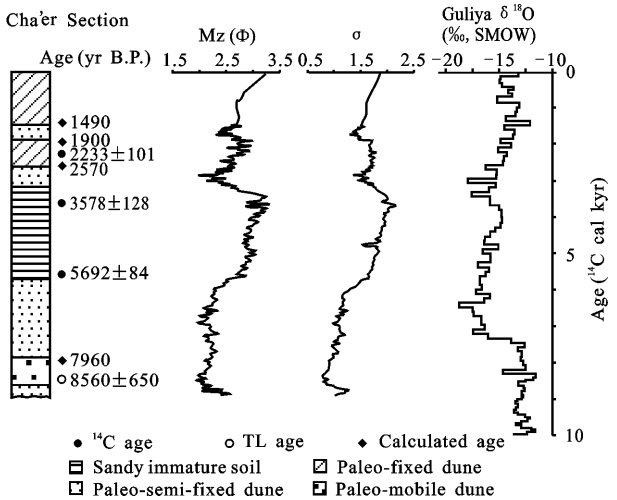
Conclusively, sediments of Cha'er Section mainly consists of sand, paleo-mobile and paleo- semi-fixed dune sands in this section are quite similar to modern aeolian sand in grain-size composition, Mz or σ distribution, indicating a similar depositional environment in the formation environment of modern sand dunes. Compared with the types of dunes above, the contents of sand substance of the paleo-fixed dunes and sandy immature soils decrease, while the contents of silt and clay increases, indicating a sand-dune fixing and soil-forming process.

4 Discussion

In this research, grain size characteristics of Cha'er section was interpreted as proxy indices of aeolian activities and paleoclimate. The analysis shows that this section is the products of climate changes and the evolution of aeolian landforms, and the environmental variation since 8600 yr B.P. along the middle reaches of the Yarlung Zangbo River could be divided into four apparent stages.

4.1 8600–5700 yr B.P.

Low value of Mz and σ curves (Fig. 4) in Stratum 7 represent coarser mean grain size and clear sorting, which suggest that between 8600 yr B.P. and 8000 yr B.P., the climate was cold and dry, with strong winds. Sediments such as aeolian sands, loess, and outcropping river silt rose in the presence of cold, drought, and strong winds leading to intensified aeolian activity, and these sediments were deposited in piedmont areas of the river valley when the wind decreased in strength. Together with activation of semi-fixed or fixed dunes, mobile sand dunes were wide spread in this period. Mean grain size of Stratum 6 is finer and sorting decreases, which indicates weakening of aeolian activity and paleoclimate became finer between 8000 yr B.P. and 5700 yr B.P., leading to deposition of fine aeolian sediments and increased vegetation coverage of bare surfaces, mobile dunes fixed in this period. These findings suggest the geomorphologic evolution of the study area between 8600 yr B.P. and 5700 yr B.P.: from mobile dunes to semi-fixed dunes.



SMOW: standard mean ocean water
Source: Thompson et al., 1997

Fig. 4 Changes in grain-size parameters of Cha'er Section and comparison with $\delta^{18}O$ curves for Guliya ice core

4.2 5700–3600 yr B.P.

Sandy immature soils (equivalent to Stratum 5) developed in the Cha'er Section from 5700 yr B.P. to 3600 yr B.P., high values of Mz and σ curves represent that the mean grain size of the sediments in this period was finer than that in others, the silt and clay contents reached their highest levels, and sorting decreases. These results indicate that the wind was weaker in this period than in the previous period and the paleoclimate was warm and wet. During this stage, with a warm and wet climate and weak winds, vegetation coverage increased on dunes, and semi-fixed dunes became fixed and began to undergo pedogenesis.

4.3 3600–1900 yr B.P.

Since 3600 yr B.P., the sediments of Cha'er Section have still been composed mostly of aeolian sands. Fluctuations in Mz and σ curves reveal climatic changes during this period. Between 3600 yr B.P. and 2600 yr B.P., equivalent to Stratum 4, low values appear in Mz and σ curves, indicating the presence of a dry, cold climate with strong winds. The fixed dunes that underwent pedogenesis during the middle of the Holocene were eroded by wind and became active once more. Between 2600 yr B.P. and 1900 yr B.P., equivalent to Stratum 3, the mean grain size decreased and sorting index increased, revealing a relatively warm and wet environment with weak winds, resulting in pedogenesis of dunes. In this stage, climate shifted from cold-dry to warm-wet, dunes shifted from the semi-fixed to fixed, but soil formation had not finished yet.

4.4 1900 yr B.P. –present

From 1900 yr B.P. to present, the environment in this area bacame fine, but cold events were obviously reflected from Mz and σ curves during the early period (1900–1500 yr B.P.). Between 1900 yr B.P. to 1500 yr B.P., equivalent to Stratum 2, data of Mz and σ curves were manifested as a second trough. The dunes that had undergone short term pedogenic processes in previous stage became mobilized again. Since 1500 yr B.P., equivalent to Stratum 1, Mz and σ curves show an increasing trend, suggesting that the climate became fine with weak winds. Mobile dunes became fixed once more and underwent pedogenesis.

The grain-size characteristics in Cha'er Section show good records of aeolian activities and environment evolution in this region. The period of dune activation is in correspondence with the low values of $\delta^{18}O$ curve in Guliya ice core (Wang et al., 2002) and low values of peat humification curve in the Hongyuan region (Wang et al., 2003), and the period of dunes fixation and pedogenesis is in correspondence with the warm and wet period recorded in the historical data (Zhu, 1973; Wang et al., 2008) and lake sediments (Zhu et al., 2008). Therefore, the grain-size characteristics suggest that aeolian activities in this region were in certain response to global climate changes, but this response mechanism remains to be studied further.

5 Conclusions

Cha'er section offers a high resolution record of aeolian sedimentation along the middle reaches of the Yarlung Zangbo River since Holocene. On the systemic analysis to grain-size characteristics of sediments and age data, the following points mark the main conclusions of this research:

(1) Cha'er Section include one stratum of paleo-mobile dunes, four strata of paleo-semi-fixed dunes, two strata of paleo-fixed dunes, one stratum of sandy immature soils. Paleo-mobile and paleo-semi-fixed dune sands are similar to modern aeolian sand both in grain-size composition and depositional environment that is reflected by Mz and σ distribution. But compared with modern aeolian sand, the contents of sand materials of the paleo-fixed dunes and sandy immature soils relatively decrease while the silt and clay increases, and the depositional environment of them are different.

(2) Grain-size characteristics of sediments in Cha'er Section reflect the paleoclimate variation and process of aeolian landform evolution since 8600 yr B.P. This process can be divided into four stages: 8600–5700 yr B.P. was a cold-dry stage with strong winds, characterized by shifting from dunes activating to dunes fixing; 5700–3600 yr B.P. was a warm and wet stage with weak winds, undergoing soil-forming processes; 3600–1900 yr B.P. was a stage with climate fluctuation, resulting in dunes activating in early period and fixing in later period; 1900 yr B.P.–present was a stage when climate bacame fine, and dunes activated at the beginning and then fixed again, which is similar with the process in previous stage.

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