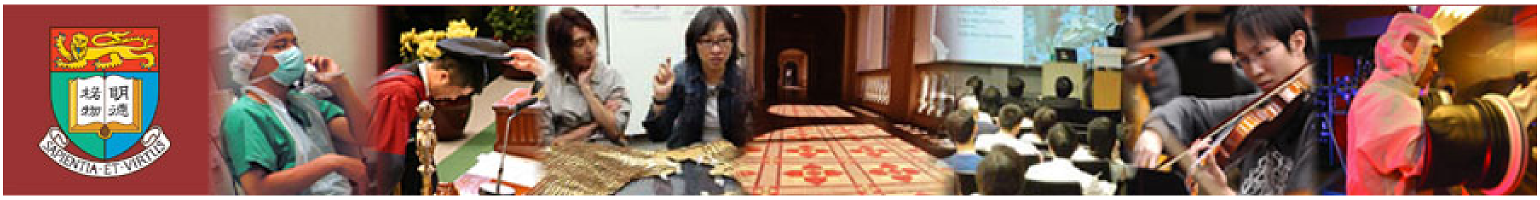

Title	**Grain-size cycles in Salawusu River valley since 150 ka BP**
Author(s)	**Zhang, Y; Li, B; Jin, H; Zhang, DD; Yan, M; Zhu, Y; Yao, C**
Citation	**Journal of Geographical Sciences, 2001, v. 11 n. 4, p. 461-472**
Issued Date	**2001**
URL	**http://hdl.handle.net/10722/86071**
Rights	**Creative Commons: Attribution 3.0 Hong Kong License**

Article ID: 1009-637X(2001)04-0461-12

Grain-size cycles in Salawusu River valley since 150 ka BP

ZHANG Yu-hong[1,2], *LI Bao-sheng*[1,2], *JIN He-ling*[3], *David Dian ZHANG*[4], *YAN Mun-cun*[5], *ZHU Yi-zhi*[1], *YAO Chun-xia*[2]

(1. State Key Lab of Loess and Quaternary Geology, Institute of Earth Environment, CAS, Xi'an 710061, China; 2. Dept. of Geography, South China Normal University, Guangzhou 510631, China; 3. Cold and Arid Regions Environmental and Engineering Research Institute, CAS, Lanzhou 730000, China; 4. Dept. of Geography and Geology, Hong Kong University; 5. Dept. of Hydraulic Engineering, Tsinghua University, Beijing 100084, China)

Abstract: The palaeo-mobile dune sands and fluvio-lacustrine facies with palaeosols in Milanggouwan stratigraphic section of the Salawusu River valley situated at the southeast of the Mu Us Desert experienced abundant remarkable alternative changes of coarse and fine rhythms in grain-size since 150 ka BP, and the grain-size parameters — Mz, σ, Sk, Kg and SC/D also respond to the situation of multi-fluctuational alternations between peak and valley values. Simultaneity the grain-size eigenvalues — Φ5, Φ16, Φ25, Φ50, Φ75, Φ84 and Φ95 are respondingly manifested as greatly cadent jumpiness. Hereby, the Milanggouwan section can be divided into 27 grain-size coarse and fine sedimentary cycles, which can be regarded as a real and integreted record of climate-geological process of desert vicissitude resulted from the alternative evolvement of the ancient winter and summer monsoons of East Asia since 150 ka BP.

Key words: Salawusu River valley; Milanggouwan section; 150 ka BP; grain-size; palaeoclimate cycles

CLC number: P531; P532; P931.3 **Document code**: A

Situated at the southeast Mu Us Desert on the Ordos Plateau of China, the Salawusu River valley, contains abundant environmental vicissitude information of the East Asia Monsoon since Late Quaternary and serves as an excellent site for researches of sedimentology and climatology etc. As early as 1924, the French paleontologists Teilhard de Chardin *et al.* found the Upper-Pleistocene Salawusu Formation and drew an outline of the "ideal section through the loessic lands of N and the SE corner of the Ordos"[1]. Since then, over 70 years, considerable studies have been made by the scholars at home and abroad, and got many significant scientific results on Late Quaternary geology[2-8], palaeontology[9-14], palaeoanthropology[15-20], desert variance[21-27] and the foundation of the Upper-Pleistocene Chengchuan Formation[28], which continuously intensifies our comprehension on the environment and its evolvement process in the region. Especially in recent years, the frequent vicissitudes' historical process in between desert and inter-desert periods disclosed by the subdivision of multi-sedimentary cycles in the past 150 ka

Received date: 2001-06-02 **Accepted date:** 2001-07-20
Foundation item: National Natural Science Foundation of China, No. 49971009; State Key Laboratory of Loess and Quaternary Geology, Institute of Earth Environment, CAS, No. SKLLQG0008; The Key National Project for Basic Research, No. G2000048701
Author: Zhang Yuhong (1974-), graduate student, specialized in environmental evolvement and engaged in geography education. E-mail: claudych@163.net

(Upper-Pleistocene—Holecene) in the Milanggouwan stratigraphic section[29] further shows that up to the present this section is the most ideal geologic memory record for exploring Late Quaternary deserts of China and their environmental evolutions.

However, can the above-cited multi-sedimentary cycles be coordinatively regarded as a result of climate cycles? Recent researches[30] and other relational discusses[31] confirm the relationship between these two, but very few is a systemic discussion on both especially according to the result of grain-size analysis in the Milanggouwan section. In light of the sedimentology, stratigraphy and palaeoclimatology, grain-size analysis just is one of the most important quantitative substituted indexes to distinguish lithology, lithofacies and ancient sedimentary environment. Therefore, the authors analysed the grain-size result of the Milanggouwan section, based upon which make a tentative discussion on the climatic cycles since 150 ka BP was made.

1 General situation of the Milanggouwan stratigraphical section

The Milanggouwan stratigraphical section is located in the left bank about 500m northeast of Milanggouwan village in the middle reaches of Salawusu River. It is, at the present, one of the most representative Late Quaternary sections in the area with continuous strata and integrated strata sequences (Figure 1). From the recent mobile dunes on the top of the Ordos Plateau surface down to the Salawusu River, the section is about 83m in thickness, and can be divided into 72 layers according to sedimentary facies, including 29 layers of eolian palaeo-mobile dunes, 3 layers of palaeo-fixed to semi-fixed dunes, 1 layer of recent mobile dunes, 28 layers of fluvio-lacustrine facies, 5 layers of brownish and drab palaeosols, 4 layers of black loam palaeosols, 2 layers of loess and 3 layers of congeliturbated folds developed after lacustrine depositions. Their ages belong to Middle Pleistocene to Holocene, including part of Lishi Formation and the formations of Salawusu, Chengchuan, Dagouwan and Dishaogouwan. Divided in terms of climate-stratigraphy they are respectively attributed to the Riss Glacial Period, Riss/Würm Interglacial Period, Würm Glacial Period and Postglacial Period, and the geologic time limits, here, of Lishi Formation/Salawusu Formation, Salawusu Formation/Chengchuan Formation, Chengchuan Formation/Dagouwan Formation are respectively 150 ka, 70ka and 10ka, corresponding one to one to those of the above-mentioned glacial and interglacial ages. In the Milanggouwan section the most pronounced lithofacies character is the eolian fossil dune layers (Figure 1), especially the palaeo-mobile dunes, and the fluvial-lacustrine facies and palaeosols come the second. Palaeo-mobile dune layers consist mainly of fine grains sandy sediment, loose and all evenly sorted. There are few palaeo-fixed to semi-fixed dune layers, chiefly being fine to very fine sands with a few contents of silt and clay, compact and moderately sorted, vertical joints developed, without bedding and often plant roots observed. Fluvio-lacustrine facies and palaeosols are mainly composed of very fine sands-silt with a few contents of clay, loose and soft to compact, badly sorted, plant roots can be observed often and the relict fossils of plant roots and leaves be seen occasionally. Usually in the bottom of fluvio-lacustrine facies and palaeosols are developed stratified calcareous concretions or calcareous plates, whose underlying strata are generally eolian dune layers. The palaeosols in the section show clear soil genesis' structure, i.e., argillic horizon in the upper, the caliches with abundant neogenic carbonate in the middle and eolian sands usually with even sorting as the parent material in the lower, sometimes fluvio-lacustrine sediments. Relatively speaking, more adhesive is the argillic horizon texture of the brownish soil than that of black loam paleosol. Polariscopic analysis and experimental results show that the microstructures with colloid spot forms of both brownish and black loam paleosol are distinct. Of which, the soil matrix in the former contains more clay particles, carbonate and ferruginous oxide, while the latter is compounded of clay and a portion of carbonate, with greyish-white calcic pseudohypha and calcium membrane. For convenient discussion, the recent mobile dune sands in the paper, palaeo-mobile dune sand, palaeo-fixed to semi-fixed dune sands, fluvial facies, lacustrine-swamp facies, palaeosols and loess are respectively denoted by MD, D, Fd, FL, LS, S and L, following the digits—the sequence numbers in the section and showing in Figure 1. There are many layers containing fossils in the section, of them ten horizons (2S, 3LS, 8LS,

14LS, 22LS, 26LS, 30LS, 48LS, 50LS, 54LS) containing mollusk fossils and three horizons (26LS, 51FD, 63LS) containing vertebrate fossils (Figure 1).

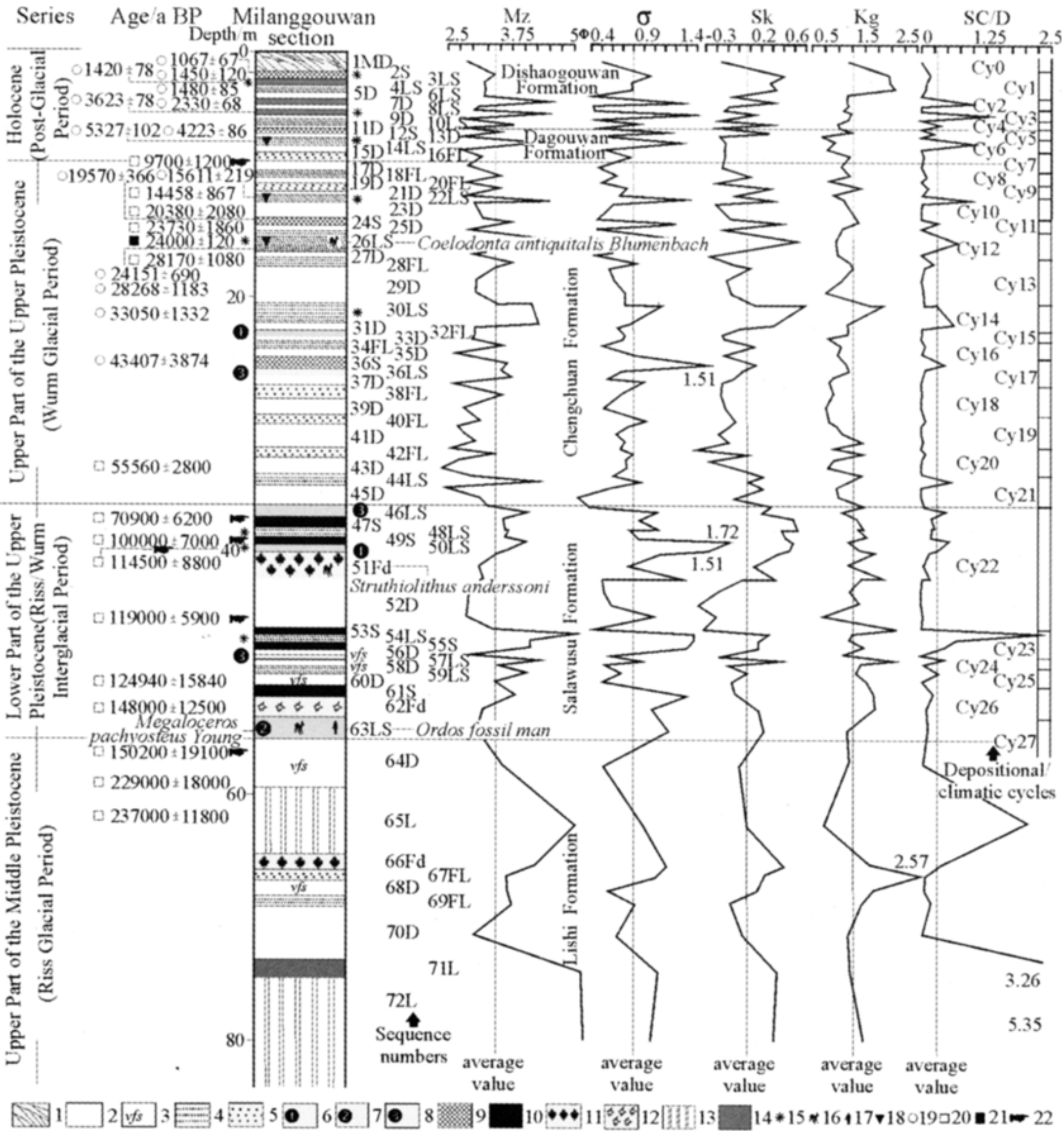

Figure 1 Milanggouwan stratigraphical section and the change of its grain-size parameters

1—recent mobile dune; 2—palaeo-mobile dune sands (fine sands); 3—palaeo-mobile dune sands (very fine sands); 4—silty very fine sands; 5—clayey fine sands (fluvial facies); 6—silty fine sands; 7—clayey-silty fine sands; 8—clayey very fine sands; 9—black loam paleosol; 10—brownish; 11—palaeo-fixed to semi-fixed dune (fine sands); 12—palaeo-fixed to semi-fixed dune (very fine sands); 13—Lishi Loess; 14—silty-clayey silt; 15—mollusk fossil; 16—vertebrate fossil; 17—Ordos Fossil Man; 18—congeliturbated fold; 19—^{14}C age; 20—TL age; 21—uranium age; 22—ages obtained by correlating with the strata concerned in the Salawusu River area[29]

It is seen from Figure 1 that, in vertical direction of the Milanggouwan section, the eolian dune sands and fluvio-lacustrine facies or/and palaeosols which overlap on each other constitute quite remarkable coarse and fine cycles, and such deposit cycles have reached 27 times since 150 ka BP.

2 Basic feature of grain-size distribution since 150 ka BP

2.1 General distributional feature of grain-size in the Milanggouwan section since 150 ka BP

The grain-size analysis samples in the Milanggouwan section were basically layer by layer collected from top to bottom according to the above-mentioned genetic facies units, while collection density was also moderately increased to some horizons with greater thickness. Altogether 95 samples were collected *in situ* and treated by mesh and pipette analyses by Zhang Huanxin and Song Weijia from the Central Laboratory, Cold and Arid Regions Environmental and Engineering Research Institute, Chinese Academy of Sciences. The classification standard of grain-size grades of the section adopted is 1-0.1 mm decimalist and < 0.1 mm the general principle of classification of Chinese loess. For convenient expression, in this article the grain-size is denoted by its logarithm Φ and the transformation formula is $\Phi = -\log_2 d$ ("d" is diameter in mm) set by W.C.Krumbien[32].

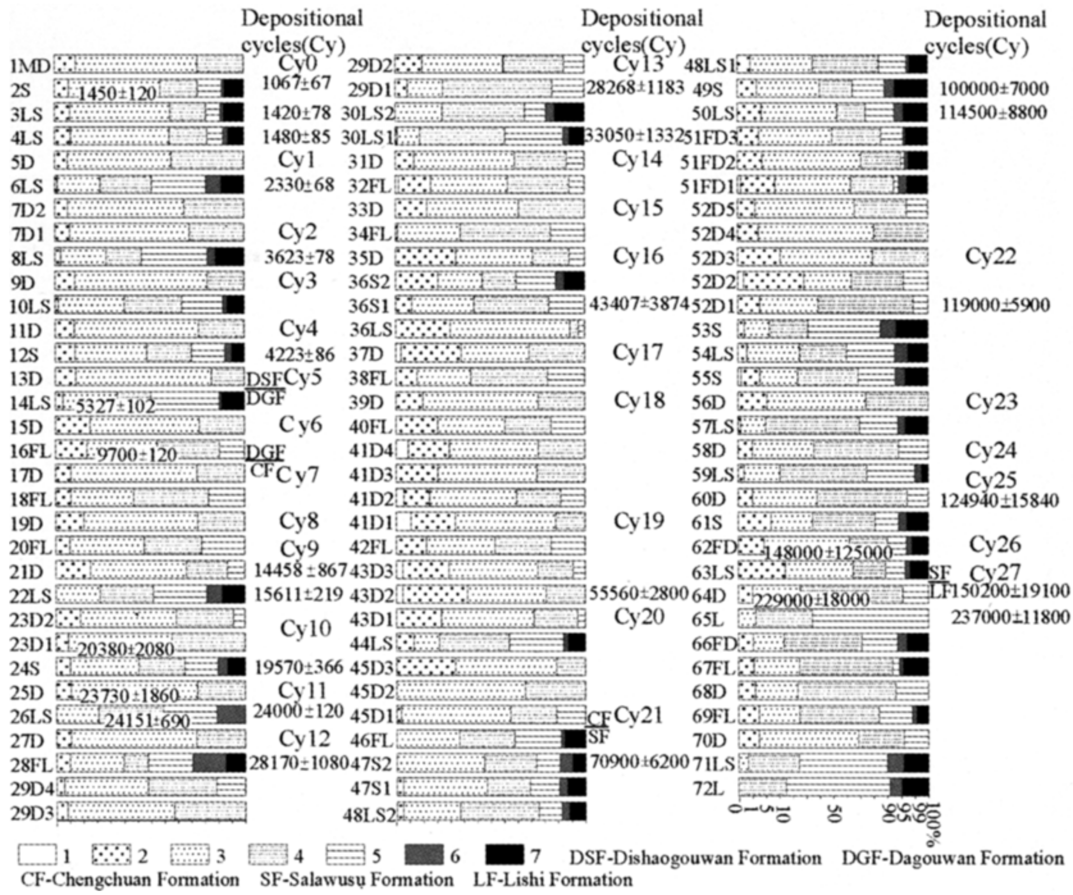

Figure 2 The grain-size accumulative centigrade content of Milanggouwan section

1—coarse sands (0-1Φ); 2—medium sands (1-2Φ); 3—fine sands (2-3.32Φ); 4—very fine sands (3.32-4.32Φ); 5—coarse silt (4.32-6.64Φ); 6—fine silt (6.64-7.64Φ); 7—clay (>7.64Φ)

On the basis of the grain-size analytical result of the Milanggouwan section, the figure of grain-size accumulative centigrade content (Figure 2) has been drawn, from which the following grain-size general distribution characteristics are displayed of the different facies in the section since 150 ka BP:

The palaeo-mobile dune sands, same in grain-size as that of the recent mobile dunes in the region and its surroundings[33], are almost all composed of sandy components. Of which the average content of fine sands is 64.95% with a distribution range of 34.16-89.57%, that of very fine sands 25.17% with a range of 5.57-59.06% and medium sands, 6.83% with a range of 0.06-32.16%. A few layers contain a little coarser silt with an average content of 1.21% and the distribution range of 0-6%. A very minute amount of coarse sands are preserved in the palaeo-mobile dunes, with only 0.1% of average content and the distribution range of 0-1.33%, but lack of fine silt and clay.

Similar to the grain-size of the recent fixed to semi-fixed dune sands in the area and, the northern margin of the Loess Plateau to its south[33], the palaeo-fixed to semi-fixed dune sands are also mainly characterized by sandy substance, and both of them have a certain proportion of silt and clay. The average contents of fine sands, very fine sands and medium sands in the dune sands are 56.03%, 27.96% and 5.15% respectively, with distribution ranges being 46.2-65.74%, 21.72-36.76% and 3.34-8.13% in turn; the average contents of the coarse silt, clay and fine silt are 6.82%, 2.69% and 1.26% respectively with distribution ranges being 1.7-9.43%, 2-3.56% and 0.67-2.47% in turn.

Also the fluvial facies are mainly characterized by sandy substance, mostly composed of very fine sands with fine sands coming next. The average content in the former is 46.02%, distribution range 32.49-65.07%, and that in the latter is 41.09%, distribution range 27.97-54.97%. There are a few coarse silt and medium sands, with an average content of 8.2% in the former and the distribution range of 1.16-17% and that of 4.42% in the latter and the range of 0.23-11.4%. Fine silt and clay content is very low, whose average values are 0.1% and 0.17% respectively and distribution range 0-1% and 0-1.56% in turn.

Like fluvial facies, the lacustrine-swampy facies are equally composed of very fine sands and fine sands come next, averaging 43.09% in content in the former and 26.49% in the latter, with distribution ranges of 22.26-76.66% and 4.44-63.33%. Difference from the fluvial facies is that the coarse silt, fine silt and clay all obviously increased in their average content, being respectively 24.09%, 2.2% and 2.76% and varying in the order of 5.13-47.3%, 0.43-5.7% and 0-5.3%. Medium sand have very low average content, being 1.57%, varying 0.12-14.2%.

The palaeosols even more approximate in grain-size to the lacustrine-swampy facies. The difference between these two mainly lies in that in the former there is a slight increase in the granule' ingredient content of fine silt and clay. In the palaeosols, the very fine sands, fine sands and coarse silt average 36.12%, 35.92% and 20.63% in turn, their distribution ranges being 24.23-54.93%, 5.93-57.7% and 7.83-56.34% severally; the fine silt and clay average 2.69% and 2.94% in turn, ranges 0-6.53% and 0-6.46% severally; also medium sands have a slight increase in content, averaging 2.8%, and relatively narrow in its distribution, varying within 0.07-10.16%.

From the above analyses, it is easy to make out of the similarities and differences in grain-size general distributional features between the eolian sands and the fluvio-lacustrine facies and palaeosols. While more conspicuous is the differences between the eolian palaeo-mobile dunes, palaeo-fixed to semi-fixed dunes and fluvio-lacustrine facies or palaeosols. Especially the fluctuations of coarse and fine rhythms are most obvious shown by the alternative actions to one another with wind and water and biochemical weathering at the grain size of vertical direction in the section.

2.2 Changes of the grain-size parameters — Mz, σ , Sk, Kg and SC/D

In order to systematically find out the relationship of the grain-size distribution regularity of the Milanggouwan section and the sedimentary palaeoclimate environment, the data of the section are calculated through the formulas of Mz (average grain size), σ (standard deviation), Sk (skewness) and Kg (kurtosis) and then counted in EXCEL. These parameters were calculated by adopting the formulas established by Folk and Ward in 1957:

$$Mz = (\Phi16+\Phi50+\Phi84)/3,$$

$$\sigma = (\Phi84-\Phi16)/4+(\Phi95-\Phi5)/6.6,$$

$$Sk = (\Phi84+\Phi16-2\Phi50)/2(\Phi84-\Phi16)+(\Phi95+\Phi5-2\Phi50)/2(\Phi95-\Phi5),$$

$$Kg = (\Phi95-\Phi5)/2.44(\Phi75-\Phi25).$$

Moreover, to farther illuminate the relationship between the sandy substance and silt and clay, the ratio of the summation of silt and clay to sands, i.e. SC/D is also calculated in the paper (Figure 1). From Figure 1 the following change characteristics can be seen in the distributions of Mz, σ , Sk, Kg and SC/D since 150 ka BP in the section:

Greater change extension is of the sedimental grain-size parameters since 150 ka BP. The distributuion ranges of Mz, σ , Sk and Kg are 2.33-5.06Φ, 0.28-1.72, −0.38-0.59, 0.68-2.11 respectively and SC/D, 0-2.26.

The grain-size parameters in various formations since 150 ka BP are rather different. Distribution ranges of Mz, σ , Sk, Kg and SC/D in Salawusu Formation are 2.83-5.06Φ, 0.43-1.72,−0.36-0.53, 0.73-2.11 and 0-2.26 respectively, with their average values of 3.56Φ, 0.95, 0.15, 1.42 and 0.28 in turn. The values in Chengchuan Formation are 2.33-4.75Φ, 0.28-1.51, − 0.38-0.59, 0.76-1.92 and 0-0.93 respectively, with average being 3.23Φ, 0.73, 0.02, 1.13 and 0.12 in turn. Those of the Dagouwan Formation and Dishaogouwan Formation are 2.73-4.49Φ, 0.41-1.39, −0.18-0.4, 0.68-2.06 and 0-1.28 respectively, with average being 3.32Φ, 0.76, 0.04, 1.24 and 0.25 in turn.

There are distinct differences in the grain-size parameters between the eolian sands and fluvio-lacustrine facies and palaeosols since 150 ka BP. The distribution ranges of Mz, σ , Sk, Kg and SC/D of palaeo-mobile dunes are 2.33-3.48Φ, 0.28-1.00, −0.38-0.29, 0.68-2.11 and 0-0.06 severally, with their average values of 2.92Φ, 0.58, −0.1, 1.12 and 0.01 in turn. Those of the palaeo-fixed to semi-fixed dune sands are 3.08-3.45Φ, 0.76-1.27, 0.14-0.35, 1.19-1.85 and 0.05-0.17 severally, with average values being 3.22Φ, 1.02, 0.25, 1.61 and 0.12 in turn. Those of the fluvial facies are 3-3.56Φ, 0.51-0.92, −0.26-0.28, 0.83-1.46 and 0.01-0.24 severally, with average being 3.38Φ, 0.74, 0.01, 1.16 and 0.1 in turn. Those of the lacustrine-swampy facies are 3.04-4.75Φ, 0.56-1.51, −0.12-0.59, 0.91-2.06 and 0.02-1.28 severally, with average being 3.98Φ, 1.03, 0.27, 1.37 and 0.49 in turn and those of the palaeosols, 3.38-5.06Φ, 0.69-1.72, −0.03-0.53, 1.15-1.94 and 0.08-2.26 severally, with average being 3.82Φ, 1.19, 0.29, 1.4 and 0.47 in turn.

Obviously whether the grain-size general distribution features of different sedimentary facies in the Milanggouwan section or the changes of various grain-size parameters clearly show that the fluvio-lacustrine facies or the palaeosols usually become finer in particle and worse in sorting than the eolian sands. As regards Sk, the former two increase obviously compared with the latter, displaying positive bias and the latter presents often approximately symmetrical distribution with fewness negative bias. In addition, the Kg of the fluvio-lacustrine facies and the palaeosols are larger than that of the eolian sands, especially palaeo-mobile dune sands.

At the vertical direction of the section, the grain-size distributional coarse and fine rhythms vary pronouncedly with the alternation of sedimentary facies. This can be clearly reflected not only from the grain-size accumulative centigrade content in the section, but also from the different grain-size parameters. The Mz, σ , Sk and Kg in the fluvio-lacustrine and palaeosols and the eolian sands separately constitute a commutative in between peak and valley values, interlocking and zigzag multi-fluctuational process curve since 150 ka BP: frequently from eolian sand to its overlying fluvio-lacustrine facies or/and palaeosols, the Mz Φ, σ and Sk increase correspondingly and the Kg heightens accordingly.

For the SC/D ratio in the Milanggouwan section, it is actually a proportional relationship of the particles >4.32Φ / <4.32Φ magnified, to which it is of a special significance to interpret intensity of the wind-drift sands during geological age. Among the 41 palaeo-mobile dune samples since 150 ka BP in the Milanggouwan section, the SC/D values are just 0 and even incline to 0. The SC/D of the palaeo-fixed to semi-fixed dunes are slightly greater than the mobile dunes and those of the fluvio-lacustrine facies and palaeosols obviously greater than the eolian sand layers. At vertical direction of the section, change step of the SC/D is basically consistent to the above-mentioned four parameters.

It is noteworthy that some previous scholars, who were unanimous to the Quaternary fluvio-lacustrine and palaeosols in the Salawusu River valley, had different views dealing with the eolian dunes especially the palaeo-mobile dunes, which were usually treated as fluvio-lacustrine facies[7,8,13]. Therefore, we compare the Mz and σ distribution of the various sedimentary facies in the Milanggouwan section with recent mobile dune sands (Figure 3). It is seen from Figure 3 that Mz and σ distribution ranges of the recent mobile dune sands in the Mu Us Desert (according to the analytical result of 56 samples) now known by us are 1.94-3.39Φ and 0.35-1.03 respectively[33] (Figure 3), to which very closed is the palaeo-mobile dune sands in the Milanggouwan section, and the Mz and σ of the latter, with a dense distribution range of 2.72-3.02Φ and 0.42-0.73 respectively, are almost in the range of the former. Comparing with it, there are great differences in the distribution ranges of the palaeo-fixed to semi-fixed dunes, fluvial facies, lacustrine-swampy facies and palaeosols, whose Mz and σ values are densely distributed in 3.48-4.55Φ and 1.41-0.68 respectively, out of the range of the recent mobile dune sands. So it is appropriate to attribute the palaeo-mobile dune sands in the section to eolian genesis.

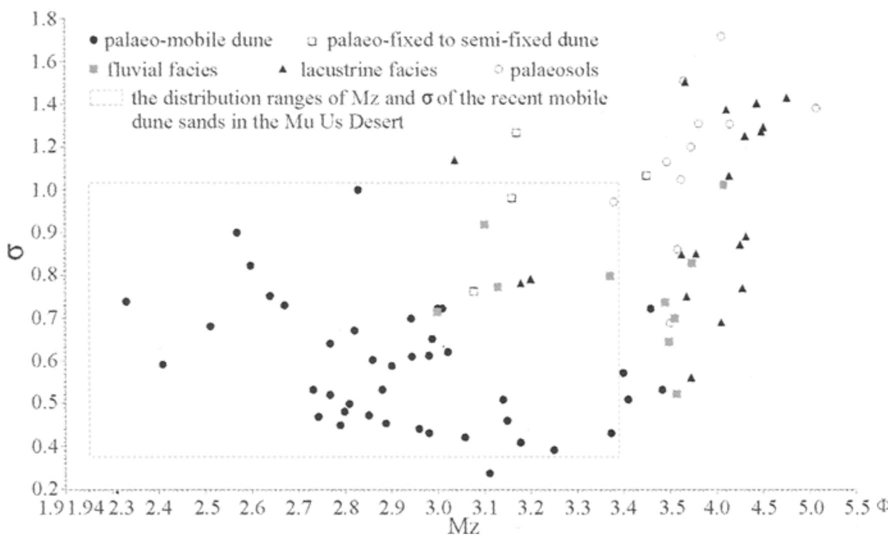

Figure 3 Mz—σ scattergram of different sedimentary facies in Milanggouwan section

2.3 Jumpiness of the grain-size eigenvalues — *Φ5, Φ16, Φ25, Φ50, Φ75, Φ84* and *Φ95*

The variations of the above-mentioned Mz, σ, Sk and Kg lie in the eigenvalues — *Φ5, Φ16, Φ25, Φ50, Φ75, Φ84, Φ95*. Obviously, the distributions of grain-size parameters of the different sedimentary facies in the Milanggouwan section and their variations are mainly restricted by these basic eigenvalues. Well then, what relationship is there between the grain-size parameters and the eigenvalues on earth? In order to answer the question, we protract Figure 4 according to the grain-size eigenvalues of 86 samples in the past 150 ka in the Milanggouwan section. At the same time, for the sake of convenient discussion, the

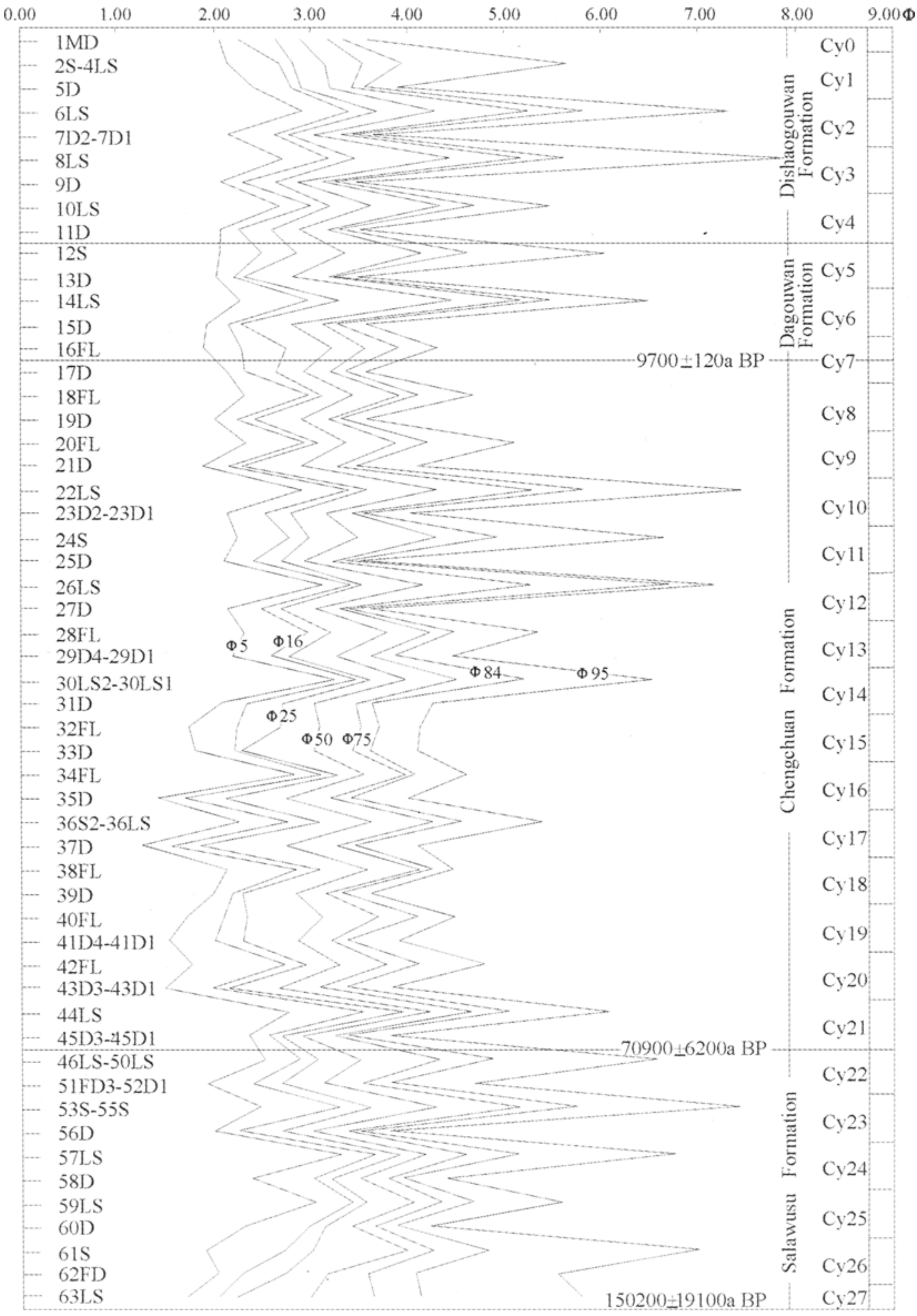

Figure 4 Changes of grain-sizes eigenvalues of Milanggouwan section

grain-size eigenvalues with several samples collected from the origin of the same stratigraphic units are averaged, shown in Figure 4. And then the figure shows 54 group samples of eigenvalues, 378 data in total, and the connections, one by one, of each eigenvalue data constitute 7 eigenvalues' change curves since 150 ka BP, existing in the 27 deposit cycles (Figure 4).

It is seen from Figure 4 that many times of "jumpiness" is the most remarkable variation of the eigenvalues of the Milanggouwan section with mutual alternations of the eolian sands with fluvio-lacustrine facies and palaeosols since 150 ka BP, and their jumpiness rhythms are nearly on the beat with those of Mz, σ, Sk and Kg. Bounding Md (median), i.e., the eigenvalue Φ50, the eigenvalues above it differ greatly from those below: the Φ75, Φ84 and Φ95 above the Md have wide jumpiness ranges, the Φ5, Φ16 and Φ25 below the Md relatively narrow, which is expatiated as follows:

Among the eigenvalues above the Md, Φ75 averages 3.8Φ with a distribution range of 2.9Φ-5.8Φ and a change extent of 2.9Φ whereas for Φ84, the three items are 4.1Φ, 3.06-6.68Φ and 3.62Φ, and for Φ95, they are 4.99Φ, they are 3.38-7.9Φ and 3.52Φ.

Among the eigenvalues below the Md, Φ5 averages 2.18Φ with a distribution range of 1.24-3.46Φ and a change extent of 2.22Φ, whereas for Φ16, they are 2.61Φ, 1.54-3.9Φ and of 2.36Φ and for Φ25, they are 2.85Φ, 1.79-4.19Φ and 2.4Φ.

In terms of the above data, it can be considered that Φ75, Φ84 and Φ95 are the eigenvalues with smartest jumpiness, which may be called "active eigenvalues" because they have high sensitivity response to sedimentary facies; in contrast with them, Φ5, Φ16 and Φ25 having low sensitivity are called "inert eigenvalues". Based on the understanding to the property relationship of grain-size parameters and all the eigenvalues, we find that after the jumpiness of the grain-size inert eigenvalues in the Milanggouwan section are restricted to a certain extent, viz. such a jumpiness extent as the above-mentioned 2.22-2.4Φ, the jumpiness extent (2.9-3.62Φ) of the active eigenvalues has become the all-important factor of fluctuation of Mz, σ, Sk and Kg. Therefore, if the grain-size parameters are said to be one of the principal parts responding to sedimentary environment, especially climate variance, the grain-size eigenvalues of Φ75, Φ84 and Φ95 are the most active individuals responding to climate variance among all the factors included. In regard to the relationship of all grain-size eigenvalues and climate, it will be expatiated in the following text.

3 Palaeo-climate cycles in the Salawusu River valley

The similarity on the grain-size general characters and Mz and σ between the palaeo-mobile dune sands in the Milanggouwan section since 150 ka BP and the recent mobile dune sands in the Mu Us Desert indicates that both sedimentary environments are alike. Palaeo-fixed to semi-fixed dune sands in the section very resemble recent fixed to semi-fixed dune sands in grain-size composition. With regard to changes of Mz and σ, their ranges in the former are respectively distributed in those (Mz 2.76-3.81Φ and σ 0.53-2.17) in the latter[33]. This may suggest that, during the course of the desert deposition, there was an appreciable quantity of seasonal precipitation which enabled herbage and shrub vegetation to grow, the barrier function of which was favourable to incept and even produce some dust and clayey granules carried during wind-driven sand accumulative periods. Therefore, it is not accidental that this kind of compact dunes bear vegetable roots, even biological relicts of the *Struthiolithus anderssoni* (Figure 1) are adaptable to arid to semiarid environment, reflecting the wind-drift sand environment with grassland and shrubs at that time differ completely from the palaeo-mobile dunes. Whether the palaeo-mobile dune sands or the palaeo-fixed to semi-fixed dune sands, that both are severally similar in grain-size to the recent mobile dune sands and the fixed to semi-fixed dune sands manifests that the two kinds of dune environments ever existed in a certain geologic times in the past, being a notable symbol of the past climatic deterioration and a distinct embodiment of the dune activation at one time though there are appreciable differences between the dune types. That is to say, in the past 150 ka the geologic process which is similar to the recent mobile dunes in the Mu Us Desert caused by arid and cold climate appeared many times in this region and the windblown geomorphologic landscapes of the fixed to semi-fixed dunes where herb and shrub vegetations grew, with a certain precipitation in the meantime, also emerged several times, while the recent dunes are only the newest episode in a long-term evolution process of the dunes in the past. For the reason given above, the dune evolution since 150 ka BP in the Milanggouwan section can be subdivided into 27 desert depositional periods, namely "desert period".

In the fluvio-lacustrine facies and the palaeosols between the dune sediments in the Milanggouwan section or both interbeds, the intervals between their uppermost and lowermost bedding planes mainly impenetrated the geological process of the fluvial action or pedogenesis, or the alternation between the two, which can be seen from the layers of 2S-4LS and 46-50LS. There were still, of course, nonperennial wind-drift sand action during the periods of fluvio-lacustrine facies and palaeosols, however it was often treated and reconstructed by fluvial action and pedogenesis soon after the formation on account of its dependence. This is perhaps one of the reasons why in the above-mentioned grain-size scatter diagram the Mz and σ values of certain fluvio-lacustrine facies and palaeosols are also distributed in the range of the recent mobile dune sands (Figure 3). Another reason probably is that the material sources before lacustrine-swamp deposition and pedogenesis are just the windblown sands and the "mother rock" acted by them. Moreover, in terms of the grain-size general distribution features of the fluvio-lacustrine facies and palaeosols that their granules increase in different degree and relative to the underlying mobile dunes can at least indicate that meanwhile, the dry wind force that transported dunes had weakened greatly. Theoretically, the extremity of fluvio-lacustrine and palaeosol development is a deposit interruptional sign of palaeo-mobile dunes. It can be seen easily, however, from the grain-size analysis result that every layer of the fluvio-lacustrine facies and palaeosol contains some content of sandy substance. Although it is difficult to distinguish what sandy substances belonged to the nonperennial windblown sands carried by fluvio-lacustrine deposits or what have taken place during the pedogenesis process, it is still of significance if the Mz and SC/D can be used to discuss the variation of dry wind force. It goes without saying that the larger the Mz Φ particularly the SC/D are, the less influence of the windblown sands especially mobile sands are of indicating lacustrine-swamp facies sedimentation and palaeosol development.

Based on the understanding to the desert period mentioned above, the fluvio-lacustrine facies and palaeosols overlying on the dunes in the Milanggouwan section can be regarded as the extremely weakened periods of desert deposit, i.e., "inter-desert period". Accordingly the section takes down the alternate evolvement process of 27 cycles of desert and inter-desert periods, and obviously they are just the above cited deposit cycles. However the problem is what relationship exists between the grain-size composition of these cycles and the past climate? To answer the question, it is necessary to comprehend and understand the deposit process of the Mu Us Desert where the site is located. It is well known that the recent wind-drift sand and dust action in the Mu Us Desert is mainly related to the winter monsoon intrusion of Asia from its north towards south and from its northwest towards southeast when the Siberia-Mongolia High Pressure enhances and pushes forward, which is resulted from temperature drop in winter and spring. In such a season, the wind-drift sand and dust action for several days' duration can make the shift forward and accumulation of mobile dunes increase obviously, and the windblown dusts continue to excurse southeastward along with the arid wind force and deposit and float on the Loess Plateau and beyond. Now that the wind-drift sand and dust action for several days' duration can attain such a scale that it can be imagined that the multi-superposition action of the winter monsoon was strong, if it was in a time consuming geologic period dominated by low temperature, the intense influence of the dry and cold climate and long period that led to the dune sand accumulations in the Milanggouwan section.

As above demonstrated from the grain-size distribution and the Mz- σ scattergram, the dune deposit in this section is windborne origin, and from reasons given above and with reference to the present seasonal wind-drift sand and dust action in question, it is not difficult to explain that whatever stage of eolian sand deposit in the past 150 ka should be also a result of multi-dynamic processes of the winter monsoon similar to that of the present Mu Us Desert. Grounded on the understanding, also it is not difficult to regard the 27 layers of dune accumulation in the Milanggouwan section since 150 ka BP as 27 desert deposit periods undergone the Mu Us Desert. On the contrary with the above, the weakening of the recent wind-drift sands and dusts in the Mu Us Desert and even stopping often due to the infiltration of the summer monsoon of East Asia from south toward north and from southeast toward northwest caused by warming up in summer and autumn, which brings more precipitation to form rivers, lakes and swamps and to make the fixation of mobile dunes because of grass growth. It can be assumed from it that if the temperature rose and persisted a long period of time since 150 ka BP, the area might be influenced by the summer monsoon more greatly and more frequently. It follows that an origin unit of fluvio-lacustrine facies or palaeosol represents a product resulted from the repeated addition of summer monsoon; the above-cited 27 sequences of fluvio-lacustrine facies and palaeosols in the Milanggouwan section is a concrete embodiment that the summer monsoons of East Asia of 27 periods formed leading to the monsoon in the Mu Us Desert. Thus, the 27 depositional cycles occurring since 150 ka BP in the Milanggouwan section can be attributed to an aftermath of the confront each other and alternative evolution of the palaeo-winter and the palaeo-summer monsoons of East Asia in the Mu Us Desert from then on.

When the winter monsoon dominated the Mu Us Desert since 150 ka BP, the wind-drift sands ran rampantly. In such a circumstance, the dust and clayey granules >4.32Φ preserved in the wind-drift sand current made of fine sands on the ground were blown away and even disappeared, which has caused the jumpiness of the eigenvalues Φ5, Φ16, Φ25, Φ75, Φ84 and Φ95 to be assembled towards Md. As a result, the particles of Mz become coarser, the sortings showed by σ better, the Sksproximately symmetrical, even negative bias, and the Kgs lower obviously, and the SC/Ds went to 0 even equal 0. In contrast, when the summer monsoon dominated the Mu Us Desert since 150 ka BP, the wind-drift sand action withered and shrinked northward, rivers, lakes and swamps developed and the pedogenesis strengthened, and along with the effect of biochemical weathering at the same time it was favorable to capture and produce more dusts and clayey granules. As a result, the particles of Mz become finer, the sortings showed by σ worse, the Sks positive bias, and the Kgs higher obviously, and the SC/Ds greater. It is just because of repeated alternations between the winter and the summer monsoons in the Mu Us Desert since 150 ka BP that have been induced the multi-cycles of deposits or to say the multi-phases of alternate evolutions between the desert periods and inter-desert periods in the Milanggouwan section, and that have caused the Φ5, Φ16, Φ25, Φ50, Φ75, Φ84 and Φ95 in the section since 150 ka BP to jump rhythmically and the Mz, σ , Sk, Kg and SC/D to fluctuate regularly.

References

[1] Teilhard de Chardin P, Licent E. On the discovery of a paleolithic industry in northern China. *Bulletin of the Geological Society of China*, 1924, **3** (1): 45-50.

[2] Teihard de Chardin P, Young C C. Preliminary observation on the pre-loessic and post-Pontian Formations in west Shansi and northern Shensi. *Geological Memoirs of China*, 1930, **1**(8): 15-17.

[3] Liu T. The composition and texture of loess. Beijing: Science Press, 1966. 9-18.

[4] Pei W, Li Y. Some tentative opinions on the problem of Sjara-Osso-Gol Series, Inner Mongolia. *Vertebrata Palasiatica*, 1964, **8** (2): 99-118.

[5] Kozlovski J K. The problem of the so-called Ordos culture in the light of the palaeolithic finds from northern China and south Mongolia. *Polia Quaternaria*, 1971, **39**: 73-75.

[6] Yuan B. Sedimentary environment and stratigraphical subdivision of Sjara-Osso-Gol Formation. *Scientia Geologica,* 1978 (3): 320 - 334.

[7] Zhou K, Li X, Shao Y *et al.* The permafrost period subdivision in the Salawusu River Reaches, Inner Mongolia, and its significance. Contribution to the Academic Symposium on the Pre-Historic Earthquake and Geology of China. Xi'an: Shaanxi Science and Technology Press, 1982. 149-153.

[8] Zheng H. Late Pleistocene fluvio-lacustrine deposits and eolian loess in North China. *Geochemica,* 1989 (4): 343-351.

[9] Teilhard de Chardin P, Licent E. On the geology of the northern, western and southern borders of the Ordos, China. *Bulletin of the Geological Society of China*, 1924, **3** (1): 37-44.
[10] Teilhard de Chardin P. Early Man in China. Beijing: The French Bookstore, Institut de Geo-Biologie, Pekin, No.7, 1941. 67-77.
[11] Qi G. Quaternary mammalian fossils from Salawusu River District, Nei Mongol (Inner Monglia). *Vertebrata Palasiatica*, 1975, **13** (4): 239-249.
[12] Li B, Dong G, Gao S *et al.* Relationship between the Malan Loess and the Salawusu Formation in the Salawusu River area, Ordos, and their geological age. *Acta Geologica Sinica*, 1987, **1** (1): 29-45.
[13] Sun J. Quaternary Geology in the Loess Plateau. Beijing: Science Press, 1991.161-168.
[14] Xie J, Gao S, Dong G *et al.* Zoocoenosium in Salawusu. *Journal of Desert Research*, 1995, **15** (4): 313-322.
[15] Licent E, Teilhard de Chardin P, B Davidson. On a presumably Pleistocene human tooth from the Sjara Osso Gol (southeastern Ordos) deposits. *Bulletin of the Geological Society of China*, 1927, **5**: 285-298.
[16] Jia L. The Ordos Fossil Man. Shanghai: Longmen United Publishing House, 1950. 1-89.
[17] Woo R. Fossil human parietal bone and femur from Ordos. *Vertebrata Palasiatica*, 1958, **2** (1): 208-210.
[18] Wang Y. The paleolithic culture of Sjara-Osso-Gol River area, Wushen Banner. Selected Writings of the Historical Relics Data, Inner Mongolia. Hohhot: Inner Mongolia Press, 1964. 9-16.
[19] Dong G, Gao S, Li B *et al.* New discovery of the Fossil Ordos Man. *Kexue Tongbao* (Chinese Science Bulletin), 1982, **27** (7): 754-758.
[20] Yuan Sixun, Chen T, Gao S *et al.* Uranium series dating of "Ordos Man" and "Sjara-Osso-Gol Culture". *Acta Anthropologica Sinica*,1983, **2** (1): 90 – 94.
[21] Dong G, Li B, Gao S *et al.* The case study of the vicissitude of Mu Us Sandy Land since the Late Pleistocene according to the Salawusu River area strata. *Journal of Desert Research*, 1983, **3** (2): 9-14.
[22] Lu X. Clay mineral composition and its relation to paleoclimate in the area of Sjara-Osso-Gol River, Inner Mongolia. *Journal of Desert Research*, 1985, **5** (2): 27-35.
[23] Gao S, Dong G, Li B *et al.* Migration and accumulation of chemical elements in the Quaternary strata of the Salawusu River area in relation to climatic evolution. *Geochemica*, 1985, (3): 269 – 275.
[24] Guan Y, Chen Z, Jia H *et al.* Ancient climate and element distribution in the Quaternary strata in Sjara Osso Gol District. *Journal of Desert Research*, 1986, **6** (1): 32-35.
[25] Shao Y. Pollen component and paleoclimate and paleovegetation in Sjara-Osso-Gol River since Late Pleistocene Epoch. *Journal of Desert Research*, 1987, **7** (2): 22-27.
[26] Li B, Dong G, Gao S *et al.* Sedimentary palaeogeographic environment of Upper Pleistocene strata and its evolution in the Salawusu River area. *Geographical Research*, 1988, **8** (2): 64-71.
[27] Li B, Dong G, Gao S *et al.* The changes in climatic environment of the Salawusu River area since the terminal stage of Mid-Pleistocene as indicated by detrital minerals in Quaternary sediments. *Acta Petrologica of Mineralogica*, 1991, **10** (1): 84-90.
[28] Li B, Dong G, Wu Z *et al.* The establishment of the Upper Pleistocene Chengchuan Formation in northern China. *Geological Review*, 1993, **39** (2): 91-100.
[29] Li B, Jin H, Lu H *et al.* Processes of the deposition and vicissitude of Mu Us Desert, China since 150ka BP. *Science in China* (*Series D*), 1998, **41** (3): 248-254.
[30] Li B, David D Z, Jin H *et al.* Palaeo-Monsoon activities of Mu Us Desert, China since 150ka: a study of the stratigraphic sequences of the Milanggouwan section, Salawusu River area. *Palaeogeography, Palaeoclimatology, Palaeoecology,* 2000, 162: 1-16.
[31] Li B, Wu Z, David D Z *et al.* The environment and change in the monsoon sandy region of China during late Pleistocene and Holocene. *Acta Geologica Sinica*, 2001, **75** (1): 127-137.
[32] Grains size analysis of sedimentary rock (sediment) and application. The Shanbei group of Chengdu Geologic Institute. Beijing: Geological Press, 1978. 1.
[33] Li B, Dong G, Gao S *et al.* Analysis and discussion on the grain size of the Quaternary stratum profile in Yulin area of the northern Shaanxi. *Acta Geographica Sinica*, 1988, **43** (2): 125-133.