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PROGRESS IN QUATERNARY AEOLIAN ENVIRONMENT RESEARCH

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ABSTRACT: Quaternary aeolian environment researches were mainly conducted by analyzing the information carriers, extracting valuable evidences about aeolian environment changes, so to presume and reconstruct paleoenvironments. This paper formulated progress in Quaternary aeolian environment research using dune-morphological records, sedimentological records and bio-fossils records, as well as advances about chronology; presented that people should pay more attention to further synthetic study of multi-types of records including dune morphology, size, formation time, sediment supply, and their relations with wind regime in future, especially the research on dating method.

KEY WORDS: Quaternary; aeolian environment research; record; chronology

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Quaternary aeolian environment (QAE for short) may be one of the natural disasters that mankind have been always facing since the beginning of the Pleistocene. In modern times, especially in recent decades, sandy desertification and sand-dust storm have become more serious, accordingly people have taken many controlling measures, and have speeded up the study on QAE. However, early studies on the history processes of aeolian environment were conducted mostly in terms of historical recordation or historical geography. And the explorations of paleoclimate, paleoenvironment and desert material origin, etc., have been limited by time. Apparently, only on the basis of Quaternary geology to study the history processes of aeolian sand, this problem can be further recognized. For this reason some research progresses on QAE in recent decades have been reviewed in this paper.

From the documentations in recent decades, it can be seen that during the Quaternary numerous dune-depositional episodes have occurred in the arid, semi-arid even semi-humid areas in the world. Many areas, such as the sandy land in the eastern China, Sahel of North Africa and the Maga-Kalahari of South Africa, the Great Plains in USA and Oman of Arabia, have experienced intensive drought and sandy desertification during the Quaternary (TCHAKERIAN, 2000; ALBELUSHI, 1998).

Extracting environmental information from the records of dune configurations, sediments and bio-fossils, with the help of dating for them, is a basic research method for QAE, from which chronological series of the evolution of aeolian environment can be reconstructed. The geological information of aeolian environment is mainly concerned with the arid and semi-arid zones in the world, especially some greater deserts. In recent decades, along with development of analytical techniques and improving of dating methods, scientists have extensively studied the deserts and reconstructed the regional or global environmental status in geological periods. This paper firstly sums up the records of dune configurations of QAE, sediments and bio-fossils, and then reviews some research advances about chronology.

1 DUNE-MORPHOLOGICAL RECORDS

Dune-morphological record is the most direct indicator of aeolian environment. Different dune configurations and dimensions can open out different wind status. By studying the configurations, dimensions and palaeovegetation of fossil dunes, QAE can be inferred.

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1.1 Dune Configuration

According to LANCASTER (1995), the presence of degraded or completely vegetated sand dunes in the areas, which are presently not subject to aeolian depositional law and at present receive mean annual rainfall values of >250mm usually, indicates that the area experienced enhanced aeolian activity in the past. This has been proved by researches on Sahle, southern Africa, Australia and the southwest of USA (TCHAKERIAN, 2000; LANCASTER, 2002). In addition, according to the difference between strike of fossil dune and modern wind regime we can deduce ancient atmospheric circulation, judge the orientation of prevailing wind and obtain the expansion or contraction of arid zone in the past (THOMAS, 1997). Under conditions of fixed sand supplying, different wind status will form dunes with diverse configurations (FRYBERGER, 1979; AHEMED *et al*., 1998).

By analyzing dune configurations, the wind regime of dune-building period can be deduced. And by precisely dating dune sediment and further understanding the relationship between modern wind regime and dune sediment, information about ancient drought degree, wind regime and regional atmospheric circulations can be gained, and accordingly the past aeolian environment can be reconstructed (AL-BELUSHI, 1998; LANCASTER *et al*., 2002; THOMAS and SHAW, 2002; GLENNIE and SINGHVI, 2002).

1.2 Dune Dimension

The size of sand dune might hold certain palaeoenvironmental significance. WARREN and ALLISON (1998) suggested that dune dimension could be a function of wind regimes that persist for long time. WILSON (1972) proposed three discrete aeolian bedform hierarchies (ripple, dune, and draa) based on grain size. Usually, dunes with height of 1−2m can reflect the quick change of wind regime (hour or day); dunes with height of 3−10m can reflect more stable wind regime (perhaps changes in year or decade); draas (or mega-dunes) formed only during very strong winds, such as the intensified winds in the tropical deserts during the Last Glacial Maximum at about 20ka (WILSON, 1972) and can reflect very stable wind regime which may keep stable for thousand years. Long time of uninterrupted sediment movement and dune growth were necessary for the formation of mega-dunes, which can only be accomplished during Milankovitch type cycles and sub-cycles (WARREN and ALLISON, 1998). This also indicates that the time scale of mega-dune formation was over ten thousand years.

1.3 Dune Vegetation

With the increase of vegetation coverage, dune activity becomes weak, so the vegetation coverage has long been considered as a sign that wind activity has weakened and sand dune has fixed. It was generally believed that the dune covered by vegetation represented stronger aeolian activity here in the past, and climate was drier meanwhile than nowadays. However, researchers found that the dune with vegetation coverage of about 30%−35% could still move when strong wind acted (ASH and WASSON, 1983). LIVINGSTONE and THOMAS (1993) suggested that seemingly some fixed dunes actually only reached a dynamic balance and would move again when conditions were slightly changed. Meanwhile, dune vegetation usually reflects the latter-day environment and it is difficult to be used to reconstruct QAE. But information about paleoenvironment still can be deduced according to types of vegetation on dune surfaces. For example, the presence of woodland vegetation on fixed dune surfaces is a reliable indicator of the extent of ancient dune fields (TCKAERIAN, 2000). In addition, numerous root crusts and remained plant roots in some strata (GAO *et al*., 1993) also can be used to deduce or judge paleoenvironment by analyzing their components or species.

2 SEDIMENTOLOGICAL RECORDS

Sediment is an environmental product and different sediment reflects different transported media and sedimentary environments. Therefore, by analyzing sediment′s characteristics, the environment then can be deduced. Sedimentological records have long been used in QAE research. Before the 1960s, people ever used granulometric characteristics to distinguish aeolian sand and probe into the deposit environment, and used the paleosol and paleo-biology to deduce the environment of grass growing and soil forming. After the 1960s, along with the development of analytical techniques and dating methods, sedimentological records were extensively used to study climatic and environmental variations. At present the sedimentological records often used in QAE research include sedimentary structures, granulometric parameters, stratigraphical sequences, contents and distribution of geochemistry elements, sandy substance colors and the micro-textures of quartz surfaces etc.

2.1 Sedimentary Structures

Sedimentary structures of dunes are direct indicators of the process of dunes building and development (PYE and TSOAR, 1990; HASI *et al*., 1999). Sedimentary structures mainly include interlaced bedding and those surface features such as wave traces, raindrop pits, etc. (FRYBERGER, 1979). The latter two were often difficult for preservation. However, according to the analyses of cross-beddings, dune morphology, dune-moving directions and deposit rates, the aeolian environment then can be deduced.

Inner structures of dunes recorded dunes′ deposit history (MCKEE, 1993). Cross-beddings of dunes are a direct indicator of earth′s surface wind, reflection of wind power, also good carrier for the variation of atmospheric circulation (YAN *et al*., 2001). The bedding dips of paleodunes can reflect wind directions of deposit periods at a certain extent (YAN *et al*., 2001; COLLINSON and THOMMPSON, 1988; DONG *et al*., 1994; ZHAO *et al*., 1988). DONG *et al*. (1994) suggested that the predominance tendency of fore-set laminae represented the primary direction of atmospheric circulation especially prevail wind regime of earth′s surface. GAO (1992) pointed out that the alternative appearances in latitudinal and longitudinal orientation of almost aclinic interlaced laminaes and plate-like, sphenoid interlaced laminaes, and wind erosion surfaces along them indicated that the paleodunes had been active. The obvious degree of aeolian interlaced stratifications and their changes can reflect the variations of wind powers and directions (DONG *et al*., 1991).

So far, however, researches using aeolian cross-beddings to reconstruct ancient airflow are still deficient. After studying the relation between airflow at leeward slope of dunes and aeolian cross-beddings, HASI *et al*. (2001) pointed out that simply using aeolian laminae directions can not precisely resume ancient wind directions except the simple cross-beddings with grain flow laminaes. To precisely resume ancient airflow direction of aeolian deposit, people must first consider the abundance status of stratification types of dunes, then the cross-bedding types and their combination and the sedimentary factors of the interface types, dips and crest line of dunes.

2.2 Granulometric Parameters

Granulometric analysis is one of the important methods to determine sedimentary facies, reconstruct paleoenvironments and research environmental changes, and it is of important significance to find out sediment sources, transportation media and power, deposit environments, as well as depositional change laws. The granulometric parameters of aeolian sediment can directly indicate wind power during deposit process, which is an important environmental index (GAO, 1992). Therefore, the research on the relations between granulometric changes of aeolian sediments and climatic variations has got broad attentions.

Granulometric parameters can reflect the dry-wet changes. Coarser aeolian grains indicate that in the deposit period the climate was dry, cold, and strongly windy; finer grains may indicate that the climate was warm, wet and weakly windy (GAO, 1992; SHI, 1991; LI *et al*., 1988). In addition, quartz psephicity is also correlative with wind status. The quartz grain with fine psephicity reflects strong ablation of wind transferring process (AL-BELUSHI, 1998). ALSHARHAN *et al*. (1998) suggested that grain psephicity presents a positive correlation with the average size of dune grains, that the sorting degree has a negative correlation with the average grain size, and that along the prevailing wind direction, both grain psephicity and sorting degree are well. By analyzing the granulometric parameters, SHAWN and PATRICK (2002) discussed the climatic characteristics of southeast Australia since 7.6ka B. P., and TCHAKERIAN and LANCASTER (2002) probed into the Quaternary environment of Mojave Desert and the north of America.

2.3 Stratigraphical Sequence

In deserts and their fringe areas, there often exist inter-bedding sedimentary sequences composed of paleosol, loess and aeolian sand. Based on different sedimentary characteristics, one may judge the environment then and there.

The appearance of paleosol reflects warmer and wetter climate in deposit period, indicating that the wind activities were weakened and dunes were fixed then. By analyzing paleosol thickness, color, grains size, magnetic susceptibility, soil forming degree as well as warm-humid conditions may be further ascertained. Loess and aeolian sand usually indicate cold and dry climatic conditions.

The existence of paleosols and carbonate in stratigraphical sequences is not only of certain significance to paleoenvironment, but also to age dating. For example, paleosols and carbonate horizons on sand ramps in the Mojave Desert can be served to establish the regional stratigraphical sequences, and to further confirm the periods of aeolian sand movement (TCHAKERIAN, 2000).

2.4 Contents and Distribution of Geochemistry Elements

Geochemistry elements′ distribution and transfer in strata are relative with sedimentary environment and its changes (LIU *et al*., 2000). The main elements used in QAE research mainly include aluminum, ferrum, manganese, kalium, natrium, calcium and silicon. They are different in weathering-leaching ratio and transfer velocity. Analyses of elements′ contents and distribution in aeolian sand can provide credible evidence for the study of aeolian environment and its evolution.

Sediment with abundant carbonate shows certain humidity and warm climate (LANCASTER, 1995). In Quaternary research, $CaCO_3$ is usually a chief indicator for carbonate, whose content mainly depends on the weathering-leaching ratio of calcium. Highly humid or dry climate is not suitable for calcium′s gathering. By contrast with it, transitional climate especially semiarid climate is most suitable for calcium dissolving, transfer and gathering (GAO *et al*., 1993; DONG *et al*., 1994). That is, gathering of $CaCO_3$ is typical characteristic of grassland environment (SHI, 1991; YAN *et al*., 1998). A relative dating system based on stages of $CaCO_3$ formation has been developed for the southwestern deserts of the United States (MACHETTE, 1985).

Aluminum is stable element in chemical nature, and often increases when climate becomes humid, and decreases when dry (GAO *et al*., 1985a, 1985b). Therefore, the strata with relatively high content of Al_2O_3 reflect the humid periods; on the contrary those with low content of Al_2O_3 reflect dry periods. The ferrum oxide in strata mainly include FeO and Fe_2O_3, and they usually display a negative correlation in contents (GAO *et al*., 1985a, 1985b), of which Fe_2O_3 content variation is accordant with Al_2O_3. MnO has same variation with Al_2O_3 and Fe_2O_3 (DONG *et al*., 1994; GAO *et al*., 1985a, 1985b). Dry condition is suitable for gathering of kalium and natrium (DONG *et al*., 1994; GAO *et al*., 1985a, 1985b). As Al_2O_3, $CaCO_3$ and organic content are easy to be lost during sand blowing, the SiO_2 has relative high content (DONG *et al*., 1994; GAO *et al*., 1985a, 1985b; WU, 1987). Therefore, silicon has highest content in the sediment formed under dry conditions.

In addition, some trace elements are also of certain significance for QAE research. Using trace elements, GAO *et al*. (2001) analyzed the climatic change in Badain Jaran Desert since the Late Pleistocene and found that although there are complicated relations between trace elements and climate, they still have great practical foreground.

2.5 Colors of Fossil Aeolian Sands

Many researches showed that the color of fossil aeolian sands is redder than modern aeolian sands (WU *et al*., 1997), and sandy substance colors can be regarded as the function of age in a degree (WU, 1987). In Mojave Desert, however, the grains on the dune slopes, over 35ka old dated by thermoluminescence method do not present the correlation between redness and age (RENDELL *et al*., 1994). As a matter of fact sandy substance colors seems to be a function of a number of complex factors including age (stability), transport distance by wind, dune type and mobility, climate (especially the variations of temperature and moisture, moisture position of dune, etc.), mineral compositions, weathering regime (Eh, pH), vegetation, and aeolian dust input (PYE and TSOAR, 1990; LANCASTER, 1995). Aeolian sands have higher reddening velocity under humid-hot conditions and the fine grains with lower psephicity can remain more redness than coarser grains with high psephicity (TCHAKERIAN, 2000). Yet, aeolian sand can redden no matter under wet or dry conditions, and grain reddening can happen at any time if the climate conditions are suitable and ground surface keep stable for a long time (LI *et al*., 1999).

2.6 Micro-texture of Quartzose Grain Surface

Micro-texture of quartzose grain surface is an important measure to distinguish sedimentary environments and judge the formation causes of sediments (SUN and AN, 2000). The environmental factors during deposit periods gave a significant impact to quartzose grain figurations. Various physical, chemical and biological processes all can leave traces on the quartz grains. As quartz rigidity is greater and its chemical property is stable, the traces can be kept for long time. Therefore, quartzose grain surface′s micro-texture can provide temporal information of the sedimentary environment, by which the depositional process can be deduced (WU, 1995). The dishing pits on the grain surface, pockmark pits and SiO_2 settling are typical characteristics of the aeolian environment (WU, 1995; LI and DONG, 1998). During the period with dry climate and frequent wind and sand activities, aeolian mechanic abrasion of quartzose grain surface is strong. In desert circumstance, chemical deposit activities of quartz surface are strong, and there are anomalous crack on the deposit layer (WU, 1987). Under humid conditions, the chemical erosion is common, and solution etchings such as erosion channel and erosion cave even some triangle delve appear along the weak part on quartz surface (WU, 1995). Research also suggested that the quartz grains with abundant secondary silicon deposition and obvious solution etchings reflect warm and humid conditions after they were deposited; that those with many aeolian traces such as crash low pits reflect dry and cold conditions (SUN and AN, 2000). However, some micro-textures of quartzose grain surface are not particular only under aeolian environment (SWEZY, 1998). Some micro-textures can be resulted from several conditions.

3 BIO-FOSSIL RECORDS

Climate can influence or determine biological distribution to a certain extent. Therefore, the paleoclimatic characteristics of the stratigraphical formation can be judged by distinguishing the bio-fossils such as spore-pollen and animal fossils, and analyzing their living conditions.

3.1 Spore-pollen Combinations

Different spore-pollen combinations in strata can reflect different environments and can provide valuable information for paleoenvironment reconstruction (ZHONG *et al*., 2001). There are few spore-pollen types and low contents in the strata formed under dry-cold conditions, but many spore-pollen types and high contents in the strata formed under warm-humid conditions. Till now, Chinese and foreign scientists have conducted many researches about spore-pollen and the QAE (YAN *et al*., 2000; SHI, 1991; SHAO and LI, 1995; ZHONG *et al*., 2000; MADEJA, 2002; MOLODKOV and BOLIKHO, 2002). Some analysis results of present surface soils show that the sporo-pollen combinations may basically reflect the vegetations *in situ* (SHI, 1991). The research also shows that the variable of spore-pollen genus has significant positive correlation with precipitation, which provides a possible method to quantitatively recover past precipitation (SHI *et al*., 1988).

3.2 Animal Fossils

Through distinguishing the animal fossils in the stratigraphical sections with aeolian sand and their living conditions, we can judge different palaeoenvironments status. By analyzing the remained animal skeleton fossils in the sediments in Namib Desert, LANCASTER (2002) proved that around 5.2ka B. P. the climatic environment was similar to that nowadays. LI *et al*. (1995) found the skull and cheek tooth of fossil *Coelodonta antiquitatis* embedded in Baiyinhushao section in Otindag Sandy Land, and drew a conclusion with reference to the chronological data that the animal fossil was buried rapidly by aeolian sand after it was died, which shows frequent aeolian activity and dry-cold climate then. XIE *et al*. (1995) analyzed 46 species of vertebrate fossils in Salawusu Valley and pointed out that the study area was a transitional zone from warm-wet forest steppe to drier desert steppe during the Late Pleistocene.

4 CHRONOLOGY RESEARCH

Precise dating is the basic precondition for paleoenvironment research, and also the necessary condition for the increase of temporal resolution and quantitative research. Therefore, chronology has long been paid a great attention to and becomes more and more perfect. According to the different time scales and temporal resolution, the dating methods used in the QAE at present include magneto-stratigraphy chronology, the dating methods of ^{14}C, ^{210}Pb, ^{137}Cs and thermoluminescence. The magneto-stratigraphy chronology is mainly used in sediment dating at long time scale, including remain magnetisms in sediment, magnetic susceptibility, dip and declination, etc. According to measured data we can construct stratigraphical polar column and compare it with the standard polar column (especially the transitional interface between the symbol polar zones, such as B/M boundary, or polar sub-zones), then we can obtain the ages of all samples through interpolation between two ages of control points. In the QAE research of China, especially longer time scale research, magneto-stratigraphy chronology was taken full advantage and has successively been used in both the eastern sandy land (GAO, 1992) and western extremely arid region of China (LI *et al*., 1998). However, the temporal resolution of magneto-stratigraphy chronology is lower and should be tested by other dating results.

^{14}C dating includes traditional ^{14}C dating and AMS ^{14}C dating. The traditional one needs larger sample quantity and long measure time, and its error is relative larger. AMS ^{14}C dating is a modern nucleus analytic method developed since the end of the 1970s (QIU, 1987). Compared with traditional ^{14}C dating, AMS ^{14}C needs fewer samples and shorter measure time. In addition, different samples dated by AMS ^{14}C can be compared to each other.

The establishment of the emendation curve of high-precision ^{14}C tree-ring age can make the ^{14}C age that is of time sequences of samples change into the calendar age, which makes the error of ^{14}C age greatly reduce (QIU and CAI, 1997). However, since ^{14}C dating is limited by time (<50ka generally), much more old strata are beyond it. Often, due to the absence of the suitable material for ^{14}C dating, also it is limited even if the stratigraphical ages are within 50ka. In addition, ^{14}C dating has a larger error for the latest several hundreds of years′ sediment (LAI *et al*., 2000). Thereby it is needed by other method to make up the deficiency.

^{210}Pb dating was first used to dating ice core of Greenland in 1963 (GOLDBERG, 1963). In recent thirty years, the method was widely used to measure latter-day's deposit rate and got delightful achievements, showing the value of ^{210}Pb dating to determine the sedimentary time within the past 100a or more (WAN, 1997, 1999). As ^{210}Pb dating is relatively precise for latter-day's deposit, it can greatly make up deficiency of ^{14}C method. Nevertheless, the transfer mechanism of ^{210}Pb in lake is still not very clear. Therefore, the result of ^{210}Pb dating must be tested by other dating methods. In most cases the man-made radioactivity nuclide ^{137}Cs is clear in deposit time and can strongly adsorb clay mineral after it was deposited. Therefore, it is often used to check ^{210}Pb age result or date sediment that cannot be dated by ^{210}Pb dating (XIANG *et al*., 1995).

^{14}C dating and ^{210}Pb dating may validate to each other, which have been used extensively. However, in desert area ^{14}C even AMS ^{14}C is still confined in the absence of carbon source.

Luminescence dating may make up the deficiency of ^{14}C and ^{210}Pb dating methods. The luminescence dating theory is that the light quantity released when crystal is affected by thermo or blazed light has a positive correlation with radiation quantity it received, and the latter has positive correlation with time (CHEN *et al*., 2003). Therefore, luminescence dating has no any request to carbon and can date for 200–300ka. Luminescence dating has got a great development for recent 40 years, meanwhile there were two developing peaks (LI, 1997). One peak appeared in the 1970s, as a new dating technology, it could determine the stratigraphical age of sample without carbon, thus attracted many scholars engaged in geomorphology and Quaternary. With the work progress, however, people noticed the complexity and some problems of the method. Thermoluminescence dating results may be affected by many factors, and the reliability and precision of the data depends on the technologists' level, experiences even the profession attitude in a great degree (CHEN, 1995). The second peak appeared after the 1980s. Since HUNTLEY (1985) supposed optically stimulated luminescence dating in 1985, the method has got a great development for it can overcome some difficulties existed in the thermoluminescence (AIKEN, 1994). Compared with the thermoluminescence the most excellence of optically stimulated luminescence is that its signal is easily solarized to approximate zero almost without the signal remain (LAI *et al*., 2000). At present, samples used in the dating are mainly quartz and feldspar. Due to abundant quartz in aeolian sand, it is the ideal sample for luminescence dating (LI, 2000). It goes without saying that luminescence dating provides a good chance for QAE research.

5 PROBLEMS AND FUTURE DIRECTIONS

The purpose to study paleoenvironment lies in understanding of the past environmental vicissitude laws, thereby to forecast the climatic change in the future. Although the studies for QAE have used various records and gained certain progresses, the most records, analysis techniques and dating precision used in QAE are confined. It cannot meet the development need in future. Synthetically analyzing the research status at home and abroad, the future directions or possible tendency for QAE are stated as follows:

(1) Synthetic study of the multi-types of records. Although some relative researches have tried to analyze comprehensively, the conclusions drawn from different records are not all coincident. As each kind of record has its own limit, how to reasonably choose record, how to comprehensively analyze record, how to reasonably match and interpret different information extracted from different records, are still await further study in the future.

(2) Research on dune morphology and its size, and their relation with formation time, sediment supply and wind regime. After the relationship in question has been understood, one can unravel formation process of the compound dunes in sand sea correctly and reconstruct palaeo-circumfluent and palaeoenvironmental situations rightly.

(3) Further research on dating method. Although optically luminescence dating provides a favorable method for the study of QAE, there are still some problems existing in the dating. The theory of crystal luminescence is still insufficiency, e.g. it is difficult for us to distinguish between light sensation trap and non-light sensation trap, research to new dosimetry instrument suitable to luminescence dating is not paid enough attention to, which need to be solved in future.

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