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CHARACTERISTICS, ORIGIN AND EVOLUTION.AGES OF AEOLIAN SAND IN THE SAHELIAN REGION OF MALI

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ABSTRACT: The Sahelian region of Mali is one of the areas seriously affected by sandy desertification in the world. Widely distributed aeolian sand lays a material basis for the development of sandy desertification. Aeolian sand in the region is dominated by fine sand, followed by very fine sand. Sand materials contained in various sand dunes are different in grain size to a certain extent and the mineral compositions of dune sand are dominated by stable and extreme stable minerals, with high stability and maturity. Aeolian sand in the region mainly comes from the reactivation of ancient sand dunes, the transportation of recent runing water and the sand supply of dry lakes and arroyos. Since the Pliocene this region has experienced four major evolution periods of aelian sand, namely from the Pliocene to the early Quaternary, last glacial period, the Holocene and present.

KEY WORDS: Sahelian region of Mali; aeolian sand; material source; desertification

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Sahel bioclimatic zone cross North Africa between 17°N and 13°N borders, the Sahara Desert to the north and the Sudan savanna to the south, being an important fragile ecological zone in the world. Since the severe Sudano-Sahelian drought of 1968 – 1973 sandy desertification has resulted in a very miserable consequences to local people, as a Sahel country in west Africa, the Republic of Mali is one of the countries most severely affected by drought and desertification. According to the investigations of the expert group of the Lanzhou Institute of Desert Research, the Chinese Academy of Sciences in 1996, the Sahelian region of north Mali covers an area of 46.088×10^4 km^2, of which 25.488×10^4 km^2 are sandy desertification land, accounting for 55.3% of its total. Of the four classes of desertified lands, slight class, moderate class, severe class and very severe class occupy 34.09%, 28.18%, 14.98% and 22.75% respectively. Various sand dunes such as linear dune (ridge), gentle undulate dune (field), barchan chain, reticulate dune, complex dune chain, coppice dune, sand sheet and eroded dune are widely distributed in the desertified region. The region has a semiarid tropical climate (Fig. 1), every year has a dry season and a rainy season, annual rainfall decreases from 600 mm in the south to 130 mm in the north, with higher temporal and spatial variability. Vegetation in the region consists of savanna sparse trees and thorny shrubs, shrub is dominated by *Acacia*; main soil types are aridisols and entisols. Extensive degraded land and desert-like natural landscape reflect that the region's sandy desertification is still in the rapid development process.

1 CHARACTERISTICS OF AEOLIAN SAND

The Sahelian region of Mali is covered with dif-

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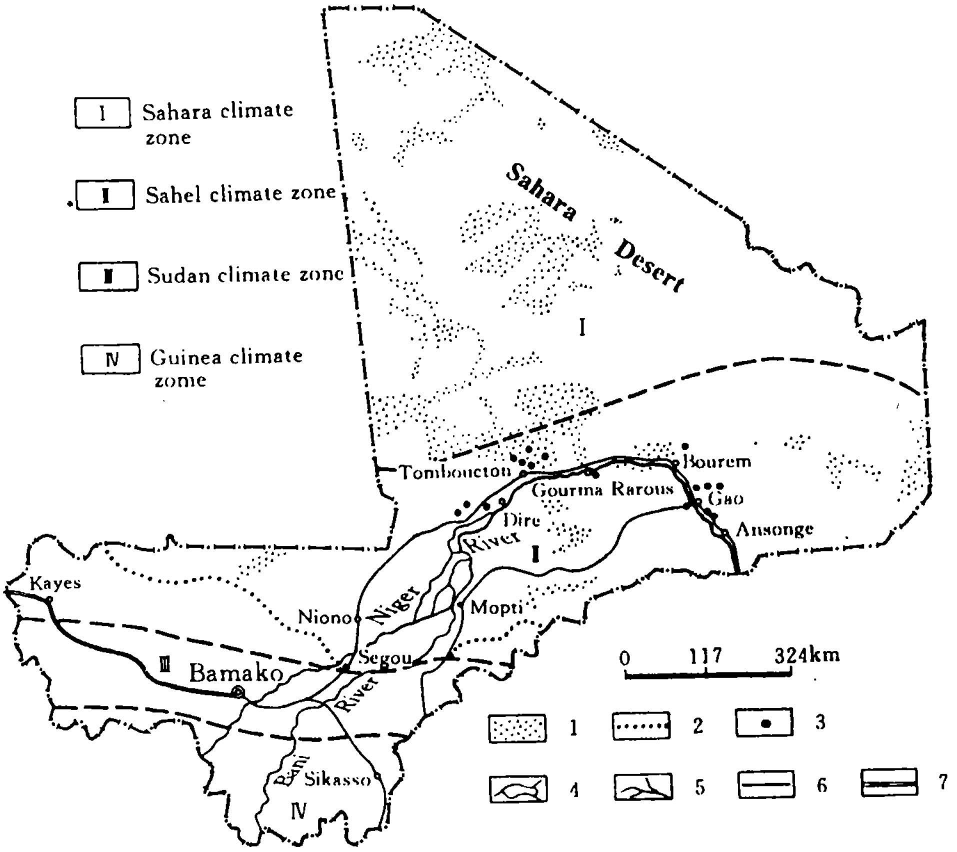

1. desert, 2. south limit of ancient dune, 3. sampling point, 4. lake, 5. river, 6. highway, 7. railway

Fig. 1 Climate zones and sampling points in Sahelian region of Mali

ferent thicknesses of loose Quaternary deposits. Aeolian sand is widely distributed in the desertified area and generally appears in orange and reddish color, while some underdeveloped aeolian sand on river and lake banks displays greyish white colour.

1.1 Grain-size of Aeolian Sand

Analytical results of grain size of sand samples collected from different dune parts in the region show that the aeolian sand composition as a whole is dominated by fine sand (0.25 – 0.10 mm), followed by very fine sand (0.10 – 0.05 mm), they account for 48.34% and 19.7% respectively, or in total occupy 60% – 80%; medium sand (0.50 – 0.25 mm) is less, coarse sand (1.00 – 0.50 mm) is very limited and almost no clay (< 0.01 mm) exists (Table 1, Fig. 2). The sand grain-size distribution and mean grain size are significantly different from place to place and from one dune type to another dune type.

Viewed from the regional distribution, the longer the transport distance down wind, the better the sorting degree and the finer the grain size, the frequency curve tends to become unimodal distribution and the skewness tends to become positive skew. Aeolian sand developed in the upwind gobi area and its margin has a wide grain-size (Mz) between 2.01 – 2.31Φ, on an average 2.28Φ, and appears as bimodal distribution. Aeolian sand distributed in the downwind delta of the Niger River has a narrow grain-size distribution, mean grain size varies between 2.32 – 2.92Φ, and its sorting degree is higher than the upwind district.

Sand grain size and sorting parameters of different types of sand dunes vary with the variations in dune shapes, vegetation conditions and intensity of deflation and deposition. As coppice dunes is an aggradated dune, obvious sorting generally does not occur due to the protection of vegetation. Coppice dune sand is very fine but has a wide grain size distribution, its mean grain size $Mz = 2.81Φ$, standard deviation $δ_1 = 0.961$, sorting is moderate or somewhat poor; frequency curve is wide and flat bimodal, skewness (SK) is symmet-

Table 1 Sand grain-size parameters of different types of sand dunes in Sahelian region of Mali

Sampling dune type	Mean grain size $Mz(\Phi)$	Standard deviation (δ_1)	Skewness (SK)	Kurtosis (KG)
Moving dune sand	2.377	0.841	0.193	0.898
Coppice dune sand	2.812	0.961	−0.038	1.038
Interdune depression sand	2.238	1.138	0.057	0.768
Ancient dune sand	2.618	0.776	−0.075	0.965

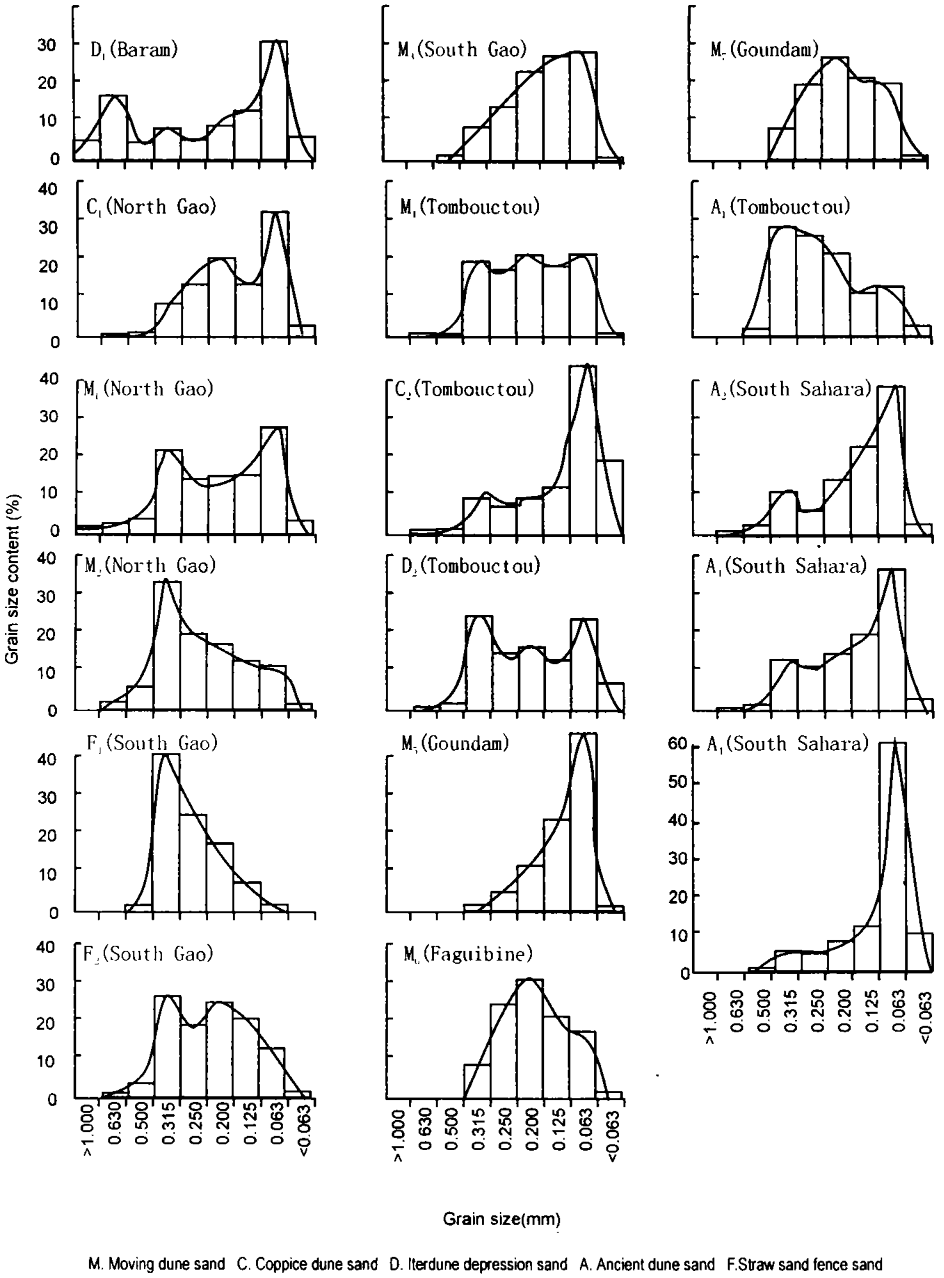

Fig. 2 Histogram of grain-size distribution and frequency curve of aeolian sand in Sahelian region

ricalor slight positive skew. Moving dune sand has coarser grain size than coppice dune sand due to continuous strong, $Mz = 2.47\Phi$, with a narrow grain size distribution; sand sorting is better than coppice dune sand, $\delta = 0.841$, belonging to moderate sorting degree; frequency curve is moderate or sharp-narrow unimodal, skewness is positive skew, suggesting a typical grain-size characteristic of aeolian sand. Interdune depressions as the transmission zone have coarser sand grains left behind during the transport processes, $Mz = 2.238\Phi$, sorting is better than recent aeolian sand, $\delta_1 = 0.776$, belonging to moderate or better sorting degree, frequency curve is mostly unimodal, suewness is negative skew. The characteristics of grain size of ancient dune sand reveal that during the formation processes of aeolian sand wind was very strong and the sorting perisisted a long time.

It can be seen from the relations among mean grain size, standard deviation, skewness and kurtosis of aeolian sand that moderate sorting occupies 83% of total sample number and poor sorting accounts for 17%. As a whole, the sorting is moderate or poor, the skewness of most samples is positive skew and negative skew, and the kurtosis of most samples is moderate and wide-flat. Various dune sands show a significant aeolian characteristics, but no obvious limit exists among them. This shows that they may be of same origin but also have some differences due to the influences of underlying material, deposition condition and development history.

1.2 Mineral Composition

Some 26 minerals have been identified in aeolian sand in the Sahelian region of Mali, light minerals mainly include quartz, orthoclase and anorthosite, chalcedony and detritus are less, of which quartz occupies 71.0% - 86.0% of the total mineral content, feldspar 14.0% - 28.5%, and the mean ratio of quartz and feldspar is 3.69. There are 21 heavy minerals, their contents vary between 0.1% - 2.0%, dominant minerals include opaque minerals (50.25% - 79.57%), zircon (8.0% - 30.25%), epidotite (0.75% - 3.0%), amphibole and pyroxene (< 0.1%). Other minerals such as garnet, andalusite, monazite, kyanite and white mica are only found in part of samples, and their contents are very low. Typomorphic minerals include zircon, tourmaline and garnet.

The comparative studies of heavy mineral composition, content and relevant parameters (Table 2) of different types of sand dunes show the following characteristics: (1) Heavy mineral varieties of various dune sands are roughly the same but their contents are somewhat different, with a mean content of 0.89%, dominant minerals include opaque minerals, zincon and epidotite. (2) Stable minerals and extreme stable minerals account for the overwhelming majority in various heavy mineral percentages, mean content of these two minerals is 97.88%, less stable minerals and instable minerals only occupy 1.939% and 0.169% respectively. The stable mineral content differs from the instable mineral contents by a few hundred times. (3) Compared with stable minerals, the instable mineral content of different dune sand shows an opposite variation tendency. (4) Heavy mineral stability coefficient (W) of aeolian sand varies between 33.78% - 56.18%. ZTR value varies between 16.75% - 30.50%. This shows that the stability and maturity of heavy minerals during the physical and chemical weathering processes, as a whole, are higher. The stabilities of moving dune sand and coppice dune sand are highest, followed by ancient dune sand and the stability of interdune depression sand is low. The maturity of ancient dune sands is highest, followed by interdune depression sand, and the maturities of moving dune sand and coppice dune sand are low.

From the preceding analysis it can be concluded

Table 2 Heavy mineral contents and their characteristic parameters (%)

Aeolian sand type	Heavy mineral content	Instable mineral content	Less stable mineral content	Stable mineral content	Extreme stable mineral content	Stability coefficient*	ZTR**
Moving dune sand	1.390	0.178	1.571	73.536	25.714	56.18	20.68
Cappice dune sand	0.695	0.375	1.375	77.750	20.500	56.14	16.75
Interdune depressions sand	1.000	0.000	2.875	75.250	21.875	33.78	21.00
Ancient dune sand	0.475	0.125	1.937	66.023	31.875	47.47	30.50
Mean	0.890	0.169	1.939	73.139	27.741		

* Heavy mineral stability coefficient (W) = (stable mineral + extreme stable mineral) / (less stable mineral + instable mineral)

** ZTR = (zircon + tourmaline + rutile) content percentage that the region is located in the savanna region with sparse trees and shrubs, various types of sand dunes have a common sand source and similar physicochemical weathering processes although their deposition environments are somewhat different. The mineral compotitions of various dune sands are roughly the same but their contents are somewhat different. On the other hand, owing to the region's hot climate, physical and chemical weatherings are very strong under high hydrothermal conditions, instable and less stable minerals are extremely easy to be disintegrated, and the stable and extreme stable minerals can be enriched and account for the overwhelming majority. Generally speaking, moving dunes are in the high-energy environment and could fully undergo the physical and chemical weathering; coppice dunes can stay in situ for many years, their instable minerals and less stable minerals could not fully undergo weathering due to the protection of vegetation. Hence, heavy minerals in moving dunes and coppice dunes have a higher stability but the mineral maturity of the former is lower than the latter. Interdune depression sand often alternately experience two high mechanical effects of wind and water, surface materials exchange frequently, physical and chemical weathering processes are instable, hence the stability of heavy minerals in interdune depression sand is low. So far as the ancient dune sand is concerned, both the maturity and stability of heavy minerals are high, this is because they experienced a long period of weathering under the high hydrothermal conditions.

2 ORIGIN OF AEOLIAN SAND

2. 1 Reactivation of Ancient Dunes

Ancient aeolian sand is the deposit formed in the geological and historical periods. It is a direct and reliable geological mark of the existence of desert (Dong *et al.*, 1983). Ancient aeolian sand distributed in southern margin of Sahara Desert and the delta of the Niger River comes from ancient dunes buried by present deposits, to date their original shapes and structure are preserved rather well. Another sand source is the exposed residual ancient dunes, their shapes and structures have been destroyed to a certain extent. The origin of these ancient dunes can be dated back to 1800 a B. P., when the climate was dry, aeolian deposition was active, numerous sand dunes were formed in today's north Sudano-Sahelian region. The subsequent climate changes resulted in the northward retreat of the desert, some ancient dunes were preserved in the forms of buried dunes and residual dunes, which no doubt constitute a hidden root for the today's desertificaiton. In recent decades, with rapid growth in population and overuse of natural resources, the pressure that human exerts on land is increasing rapidly, coupling with consecutive years of severe drought since the early 1970s, the destruction of vegegation and soil structure in the region is increasingly aggravated, which leads to the reactivation of ancient dunes, thus forming the source area of present aeolian sand.

2. 2 Transportation of Present Running Water

The mid-east part of the Sahelian region of Mali is a vast alluvial plain formed by the Niger River and the Bani River. The banks and flood basins of these two rivers are the main source areas of present aeolian sand. The mid-stream section of the Niger River between Koulikoro and Niger's border is 1428 km long, it forms a large arc bending northward and the Bani River on its south bank joins the main stream at Mopti. At the inner side of the large arc there is a dense river network, while the outer side of the large arc is the northern desert with many intermittent rivers and wadis. Below the Koulikoro the river bed turns from rock into sand, hence the channel width varies greatly. Owing to strong evaporation in this section and large water storage in the lake marshes at the inner side of the large arc, the main stream discharge flowing toward lower reaches decreases largely. The mean discharge recorded at Koulikoro Station is 1550 m^3/s, the corresponding figure at Dire Station is 1180 m^3/s. The longitudinal gradient of the river bed is small, above the Mopti is about 5×10^{-5} and below the Mopti is $(3-1) \times 10^{-5}$, water runs slowly and thus causing sediment deposition and forming a 8×10^4 km^2 inland delta of the Niger River. Calculated by the observation data at mid-stream hydrological stations of the Niger River, annual sediment deposition rate on the delta could reach up to 100×10^4 t. In addition, owing to the existence of dry season and rainy season, the runoff and flood volume of the Niger River in flood period and drought period differ very markely (Fig. 3). The maximum daily discharge range at Koulikoro Station varies between 4010 – 9700 m^3/s, the corresponding water

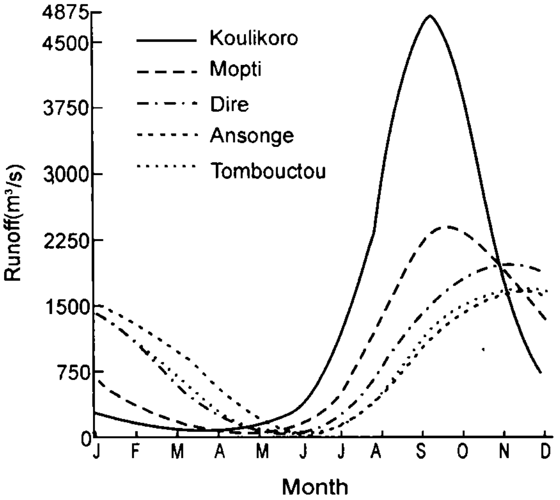

Fig. 3 Runoff of the Niger River observed at main hydrological stations in inland delta

level fluctuation is 3. 05 m. During the flood period river water overflows and form a 400-km-long and 100-km-wide flood area. On the contrary, during the drought period, the flood retreats, water level drops down, valley flat and flood basin expose to the wind, large quantity of sand is continuously transported to the river banks, which provide abundant sand material for the formation of sand dunes on the alluvial plain.

2. 3 Sand Supply of Dry Lakes and Old Channels

The middle reach of the Niger River, located in the mid-west part of the region, is a typical inland shallow-lake basin. The ancient Macina Lake basin is the main body of the basin, and the lake groups distributed to the south of Tombouctou are the remains of ancient lakes. Since the Pliocene the climate in the region had alternately experienced several arid and wet periods, the lake basin also shrank and expanded correspondingly(SU *et al.*, 1983). Since the severe drought in the early 1970s, the incoming flow in the region has greatly decreased, many lakes have dried up and part of channel has no longer conveyed any water. Sand coming from such dry lakes and river beds lays abundant material basis for the development of sandy desertification. For instance, Faguibine Lake with an area of 530 km^2 has dried up due to sharply decreased inflow and channal siltation by sand. Similarly, larger oscillation also occurs in the channel of the Niger River due to the variations of river discharge and erosion-deposition processes. For example, the Tombouctou used to be a riverside city, today it is 11. 5 km away from the river due to southward migration of the river. Sand on the ancient channels is of local origin, which also provide a sand source for the expansion of sandy desertificaiton.

3 EVOLUTION AGES OF AEOLIAN SAND

Earlier studies and present investigation indicate that since the Pliocene the Sahelian region of Mali has experienced at least four major development periods of aeolian sand.

3. 1 Aeolian Sand Development During the Pliocene and Early Quaternary

During the mid-late periold of the Miocene the globe entered the Cenozoic Ice Age, the extensive west Africa became arid, with the rapid built-up of the Antarctic ice cap it reached present scale and entered full ice cap time. During the salinity crisis event period from 6. 4 Ma B. P. to 4. 6 Ma B. P. the sea level fell about 70 m, climate further became arid and its influence extended to the North Africa, South Europe and East Africa(CHEN *et al.*, 1991) . Owing to the arid climatic influences the discharge of the Niger River upstream of the Senegal River decreased, the water way was silted up, and the encroachment of the Sokolo dunes forced the river to deflect east and flow into Macina Lake(SU *et al.*, 1983) . The thick-layer lacustrine deposits occurred during the Pliocene – early Quaternary formed the inland delta of the Niger River. In the meantime, with the formation and expansion of frigid zone, the Northern Hemisphere formed the climatic zone roughly similar to present one, and the Sahara bioclimatic zone also gradually formed in the subtropical zone(LE, 1992) . Under the influences of subtropic dynamical high pressure, the inland delta of the Niger River became arid and windy, and the river and lacustrine deposits formed into ancient dunes. Analysis showed that river-lake deposits and aeolian sand were alternately deposited in the transverse direction and the sand dunes, rivers and lakes showed an alternately distributed pattern in time. During the optimal early Quaternary period, the climate was humid, the discharge of the Niger River increased, its overflow flowed southeast and formed a new river, near Gao it joined with south-flowing river on the norther plateau and formed the exterior river, just then the early development of aeolian sand ended.

3.2 Aeolian Sand Development During Last Glacial Period

Last glacial period is one of the major periods of aeolian sand development in the region, especially in the last glacial maximum aeolian sand development was fairly widespread. According to PETIMAIL, during 35 – 21 ka B. P. small swamps widely developed in the Sahelian region, thereafter some shallow lakes in north part of the region dried up due to evaporation, river in the Sahara Desert also dried up and hence the desert extended southward. Around 15 ka B. P. the desert had extended about 400 km south of present boundary and the arid land area in the Sahelian region was 250×10^4 km^2 larger than present day, or an increase of 650×10^4 km^2 over last warm periold, the 100 mm isohyet shifted south to 13°N, the *Acacia* savanna limit extended to 10°N (PETIT-MAIRE, 1991; SARNTHEIN *et al.*, 1981), until the last glation ablation period the Sahara Desert retreated northward. The stratigraphical sequence studies revealed that there is a widespread underlying greyish white silt layer existing in the interdune depressions north of Tombouctou, the middle part is a 30 – 40-cm-thick grey clay layer (top layer is 10 230 ± 130 a B. P. in ^{14}C age) and the surface is covered by moving aeolian sand (Fig. 4). This implies that river network and lakes were widely developed in the north depression of Sahelian region during the glacial ablation period, in the Younger Dryas stage between 11.2 – 10.2 ka B. P. the region experienced a significant wet and cold climate, rivers and lakes became shallow, interdune depressions experienced widespread swamping processes and formed calcareous lacustrine deposits. From the lithologic character and structure of the grey clay it can be inferred that during the clay deposition period the temperature in the region decreased by 5℃ – 7℃.

3.3 Aeolian Sand Development during the Holocene

The Holocene is a frequently changed period of the globle climate, arid and wet events occurred continuouly in the south-Sahara and Sahelian regions. During this period the region experienced three major aeolian sand development stages:

(1) Aeolian sand edevelopment during the early Holocene

During 10.3 – 9.2 ka B. P. the region entered the Holocene warming period, although air temperature rose, rainfall was low. According to the studies of cores collected from lakes in the middle part of the Sahelian region by DURAND A. *et al.*, ① the annual rainfall in that time was less than 20 mm. Though the region had a little more rainfall, the climate was dry, hence many lakes dried up and aeolian sand developed widely.

(2) Aeolian sand development during the mid-Holocene

During 9.2 – 3.5 ka B. P. the region entered the Holocene wet period. The period between 9.2 – 6.8 ka B. P. had an optimal climate, when rainfall increased, some large permanent lakes and swamps occurred, Saharan vegetation and some large mammal population retreated in the vicinity of 22°N; large tract of moving sand in the Sahara Desert north of Tombouctou was stabilized by vegetation, some animals such as giraffe, gazette, rhinoceros and hippopotamus occured (PETIT-MAIRE, *et al.*, 1988). The weak sandy paleosol (7230 ± 120 a B. P. in ^{14}C age) developed in the south of Faguibine Lake might be viewed as the product of the wet climatic environment of that period (Fig. 4b). During 6.8 – 5.8 ka B. P. the climate in the Sahelian region of Mali greatly changed, rainfall decreased, drought events were frequent and aeolian sand deposition was active. The thick brownish yellow aeolian sand layer (Fig. 4c), with a TL age of 6.2 ± 0.5 ka B. P. occurred in the ancient dune profile north of Tombouctou, and the lacustrine salt-bearing layers (FABRE *et al.*, 1988) are the records of these drought and salinization events. The aeolian sand development stage lasted about 1000 years until 5.8 ka B. P. another less significant wet stage started.

(3) Aeolian sand development during the late Holocene

During 3.5 – 1.8 ka B. P. the climate in north Mali became arid, rainfall decreased sharply, the Sahara Desert advanced southward by about 10 degrees latitude. Aeolian sand deposition expanded in Sahelian region, the southern limit of ancient dunes extended in the Sudan savanna and reached the Segou region ② (Fig. 1). From 1.8 ka B. P. to present the northern limit of

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① DURAND A, LARG J. Bull Soc. Geol, 1986, Fr, 2 – 2

② The Lanzhou Institute of Desert Research, Chinese Academy of Sciences, Feasibility Study Report on the Establishment of Green Screen in Mali, 1998.

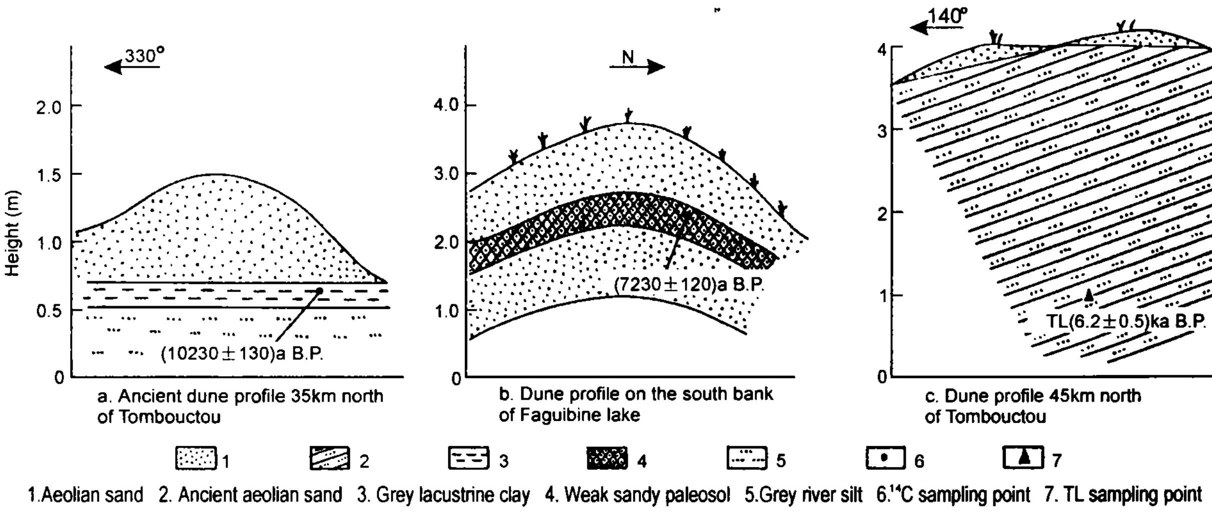

Fig. 4 Sand dune profiles in the Sahelian region of Mali

the Sahelian region gradually reached the today's 17°N.

3.4 Development of Present Aeolian Sand

Since the early 20th century the Sahelian region of Mali and the Sudan savanna were hit by three extreme severe droughts, namely 1910 – 1915 drought, 1940 – 1944 drought and 1968 – 1990 drought. Taking Gao in the east part of the region as an example, annual mean rainfall from 1961 to 1995 was 185.7 mm; during the 34-year period only one-third had an annual rainfall exceeding 150 mm, the rest years were low-rainfall years, 1987 had a lowest rainfall, only 54.6 mm, rainfall anomaly percentage reached up to – 70.59%. Rainfall in dry years decreased greatly, the isohyet might shift south by 100 – 200 km, vegetation cover declined greatly, soil structure might be destroyed seriously, the structural stability of environment system lost balance severely, all these lead to the widespread development of present aeolian sand and land desertification.

4 CONCLUSIONS

As described above, the Sahelian region of Mali is located in an important fragile ecological zone of the globe, sandy desertification area in the region is about 25.488×10^4 km^2, accounting for 55.3% of its total, and the sandy desertification shows a rapid development tendency. Widely distributed aeolian sand lays a material basis for the development of sandy desertification. Various aeolian sands have their own characteristics in the grain-size composition, mineral composition, origin and evolution ages.

(1) Aeolian sand in the region is dominated by fine sand, folliwed by very fine sand, they account for 60% – 80% of the total sand content. The sorting degree as a whole is moderate or somewhat poor, skewness is positive skew or negative skew, kurtosis is moderate and wide-flat; for the moving sand, $Mz = 2.77\Phi$, $\delta_1 = 0.841$; for the coppice dune sand, $Mz = 2.812\Phi$, $\delta_1 = 0.961$; The grain-size characteristics of various dune sand are different to a certain extent due to the influences of origin, deposition condition and evolution history.

(2) Some 26 minerals have been identified in the aeolian sand, among them heavy minerals occupy 21 species, with a content varing between 0.1% – 2.0% and dominant minerals of opaque minerals, zircon and epidotite. In the heavy minerals stable and extreme stable minerals hold the over-whelming majority, their stability coefficients (*W*) and *ZTR* value are 33.78% – 56.18% and 16.75% – 30.50% respectively. This shows that heavy minerals have a higher stability and maturity. Situated in the tropic zone, the region has higher kinetic energy and hydrothermal conditions, physical and chemical weatherings are strong, and the climatic conditions are the main factors responsible for

the mineral composition characteristics of aeolian sand.

(3) Present aeolian sand mainly comes from the reactivation of ancient dunes, the transportation of present running water, and the sand supply of dry lakes and ancient riverbed. This is quite similar to the origin of present aeolian sand in other regions of the world, including mixed agropastoral region of north China. However, because the region is mainly located in the slowly deposited alluvial plain, the aeolian sand mainly comes from the present river and lake deposits transformed by wind.

(4) Preliminary studies show that this region at least experienced four major development periods of aeolian sand, namely the Pliocene – early Quaternary, last glacial period, the Holocene and present day, among them the Holocene aeolian sand development period includes three stages, i. e. early Holocene stage (10. 3—9. 2 ka B. P.), mid-Holocene stage (6. 8—5. 8 ka B. P.) and late Holocene stage (3. 5—1. 8 ka B. P.). Owing to global climate changes desertificaiton in the region is developing rapidly. This shows that during the global desiccation pocesses the Sahelian bioclimatic zone was alternately affected by global arid and wet climate changes and experienced an ordinal but fluctuated aeolian sand develpment, expansion ⇌ fixation, and soil formation processes. Furthermore, such evolution processes roughly synchronized with those in the mixed agropastoral region of north China (DONG *et al.*, 1991; DONG *et al.*, 1995; PU, 1991).

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