Regularity of paleowind directions of the Early Cretaceous Desert in Ordos Basin and climatic significance

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Abstract By the measurement of the wind directional indicator of the Cretaceous desert in Ordos Basin, the regularity of the paleoprevailing wind directions and pattern of the paleowind belts are revealed. It is considered that the desert was controlled by a planetary wind system. In the early stage, the subtropical high pressure zone drifted south and northwards with short cycles, resulting in the alternation of westerlies and northeast trades; in the late stage, the subtropical high pressure zone drifted southwards with a long cycle, placing the desert under the westerly belt and making the desert completely controlled by the westerly belt. The reconstruction of the paleowind belts has provided the evidence of the general circulation of the atmosphere for the pattern of the circulation before the uplift of the Tibetan Plateau.

Keywords: Early Cretaceous desert, regularity of paleowind directions, pattern of paleowind belts.

The global climatic change study is a hot point today. As the pattern of the general circulation of the atmosphere is the key factor for climate, the reconstruction of the pattern of the past general circulation of the atmosphere has become an important part of the global climatic change study. The paleowind belts are a component of the past general circulation of the atmosphere and also the records of the circulation. Therefore, their reconstruction will be helpful to the reconstruction of the general circulation of the atmosphere. In recent years, the pattern of the general circulation of the atmosphere has attracted great attention of scientists. For example, Zhang[1] and Liu[2], based on the existence and inexistence of the Tibetan Plateau and paleogeography, divide the evolution of the general circulation of the atmosphere in eastern Asia into two stages: the planetary wind stage before the uplift of the plateau and the monsoon stage after the uplift of the plateau which is subdivided into ancient monsoon and modern monsoon stages. While Dong et al., Jiang et al. and Cooke et al.[3—7], based on the latitudinal distribution of the Cretaceous and Tertiary deserts and the generation of arid climate, suggest that there was a subtropical high pressure zone across the eastern Asia and a planetary wind system, but have not found any direct record of the circulation. It is true that before the Early Tertiary, not only organism, but also inorganism, i. e. biogeography and lithogeography, show strong zonal distribution. It can only indicate that zonal climate was evident at that time. Of course, as the climate is the result of the influences on the ground by zones of the circulation, it is reasonable to deduce the existence of zonal circulation, i. e. the existene of the planetary wind system, from the zonal climate. But it would be much better if direct record of planetary wind system were found. Prevailing winds are the main geological agent for a desert which must leave deep stamps on the desert. The stamps on modern desert are reflected by dune migrating directions and on paleodesert by foreset dip directions. It is the most direct geological record for reconstructing paleowind belts and has been extensively used to reconstruct paleowind belts, paleogeography, paleoclimate and even to check the paleolatitude determined by paleomagnetism (cf. ref. [8]).

The Early Cretaceous desert in Ordos Basin is located on the north margin of the subtropical arid belt[9—11], and is a part of "a red desert belt stretching across the center of China from northwest to southeast"[3, 12]. It is agreed that this desert belt was related to the location of the subtropical high pressure zone, i. e. a regional desert belt controlled by planetary winds. The purpose of this paper is, based on the measurement of paleowind direction of the Early Cretaceous desert basin, to reconstruct the pattern of the paleowind belts and to provide further evidence for the conclusion mentioned above.

The Cretaceous in Ordos Basin is mainly formed by Zhidan Group which is subdivided in an ascending order into Yujun Formation, Luohe Formation, Huanhe-Huachi Formation, Luohandong Formation and Jingchuan Formation, among which Luohe Formation and Luohandong Formation are the chief desert strata[3, 5, 6, 12—15]. Therefore, they are the target horizons of this paper.

1 Method and result of measurement

(i) Scales, life spans and preserving possibilities of eolian bedforms and the relationship to the prevailing wind direction. Three orders of eolian bedforms can be recognised: ①microforms-wind ripples (spacing 0.1—1m, spanning hours or days); ②mesoforms—dunes (spacing 50—500 m, spanning 10—10^2 years); ③macroforms—draas(spacing$>$500 m, spanning 10^3—10^5 years). Ripples are formed by individual dynamic event, dunes are formed by seasonal-scale patterns of wind direction and velocity and spatial changes in wind over larger bedforms, while draas are formed by the overall geomorphological regime and local airflow conditions. Their migrating speeds are quite different. Ripples migrate several meters an hour, dunes migrate several meters in one year, and draas migrate only a few centimeters in one year. Therefore, draas are the most sensitive bedforms to paleoprevailing wind directions, dunes are the second, and ripples cannot reflect paleoprevailing wind directions. Consequently, the migrating directions of draas and dunes are used to reconstruct the paleowind directions by measuring the dips of their foresets. The foreset cross-beds of draas are usually bounded by super or first order bounding surfaces, showing large tabular-planar cross-beds which are easy to be recognised. The study and measurement of modern deserts show that the foresets of a draa are very stable and concentric, while the foresets of dunes are much more changeable and even reversible. However, in geological records, the foresets of dunes often superimposed on draas are difficult to be preserved due to erosion by the migration of new draas over them. Most bedforms in the study basin are draas. And dunes are very limited, sometimes preserved in local horizons or on the tops of draa sequences (for instance, on the top of the 34th horizon in Yongning section). Therefore, the dips of foresets in study basin can reflect long periodic changes of paleoprevailings.

(ii) Identification of dune types and relationship to prevailings. There are many ways of dune type division. Among them, Wu's division[17] is based on dune shapes and the relationship to wind regimes: ① transverse type——including transverse dune, barchan dune and parabolic dune, the extending directions of them are normal or at 60°—90° to the resultant wind directions; ② longitudinal dune——the extending directions of it are parallel or at <30° to the resultant wind directions; ③ dunes formed by winds from several directions such as star dune——it is not parallel or normal to any resultant wind direction. According to this, the transverse types are most significant to the reconstruction of wind directions. The identification of ancient dune types are based on shapes of sand bodies and types of cross-beddings. Mckee's study[18] shows that the cross-bedding units of barchan dune are tabular-planar in shape, spread angle of foreset dips is less than 150°, only a few are 60°, the cross-bedding units of transverse dunes are also tabular planar in shape, the spread angle of foreset dips is the least of all type dunes with one well-developed maximum in the direction of the prevailing wind; the dips of the foreset cross-beddings of a parabolic dune are very gentle and the spread angle of dips can reach 200°; the dips of the foreset cross-bedding of longitudinal dune are bimodel with almost 180° apart, and the internal structures of cross-bedding units show tepee form. The measured sections (figs.1, 2) show that most of dune cross-bedding units are very thick, tabular-planar shaped with dip spread angles less than 60° and unimodel distribution. Only a few horizons have large dip spread angles with bimodel distribution, for example, the spread angle of dips in the 9th, 18th horizons in section ⑤ are 150° and 110°, respectively. According to the criteria mentioned above, the types of dunes in study sections are mostly transverse dunes and rarely barchan dunes. Although Li et al.[12] have found some longitudinal and star dunes, generally, transverse dunes are dominant. Thus the dune types studied may reflect the prevailing wind directions. Glennie suggests that plots of cross-beddings on the polar net can be helpful in the identification of dune types[19]. This method has been used here and the results are the same with the analysis above. Due to the limitation of space, no figures are shown in this paper.

(iii) Revision of dips of foresets and formation of roses. As the thickness of each cross-bedding unit is great, and the bounding surfaces are planar and far extending, each unit must have represented an individual dune migrating event. Thus, in order to collect as many as possible data, we traced along the strike as far as possible. Consequently, the data from different cross-bedding units are quite different. According to Collinson and Thompson[20], the graphical presentation for paleocurrent direction has two main methods: radial line diagrams and rose diagrams with direction class intervals of 10°, 15°, 20° or 30°. As the amount of data is large, rose diagram is used in this paper with 15° class interval. For the data from different cross-bedding units are different, if coordinate scale is used, the sizes of roses will be greatly different. Therefore, in every rose, the data with the highest frequency is taken as 100%, and the frequencies in the rest intervals are compared with the highest frequency to decide the length of each histogram.

The tectonic and paleogeographic studies have indicated that eastern China has been rotating clockwise since the Cretaceous[21, 22], but the angles are quite different. Cheng's result is 0° [23], Fang et al.'s is 8°—20° [24], Ma's is 16° [25]. Thus, in order to approach the original attitudes, 15° is taken for revision and the roses here are rotated 15° anticlockwise. Polar net ploting is not needed as the horizon in studied sections is nearly level with angle less than 5° . 10 sections were measured, 8 in Luohe Formation and 2 in Luohandong Formation. Only some sections are attached. The dips of cross-beddings in Luohandong Formation is uniform, only integrated roses are made (fig.1), while the dips of cross-beddings in Luohe Formation are more changeable, roses of every unit are made to show the changes (fig. 2).

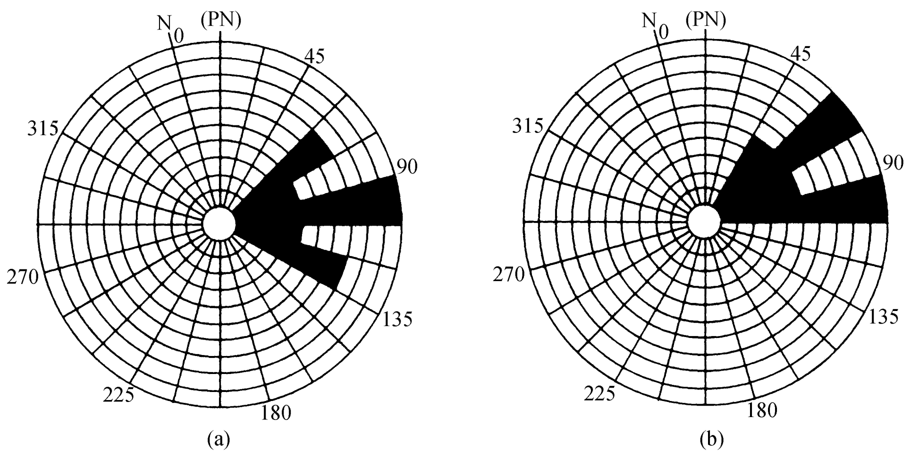

Fig. 1. Integrated roses of foreset dips of dunes in Early Cretaceous Luohandong Formation in Ordos Basin (revised by 15° anticlockwise rotation). (a) Luohandong section in Jinchuan (N = 9); (b) Fangshan section in Zhengyuan (N =7).

(iv) Section introduction and wind direction determination. The dune sediment in the desert sequence of Luohandong Formation in Jinchuan section is poorly developed but sand sheet and wet indertune sediments are well developed. According to incomplete statistics, dune cross-bedding units are 13. The dune sediment in the upper part of the sequence was reformed by water and, as a result, detorted structures and wet interdune are very well developed. As the dune units are relatively small, the dune sizes may be small. At the top of the sequence, the eolian environment was transisting upwards to be fluviolacustrine facies in overlying Jinchuan Formation. In the middle and lower parts of the sequence, both dunes and sand sheets are very well developed. Each dune cross-bedding unit can be several meters thick. Many ripple lences can be seen in the sand sheet. Above all, the sequence might be formed in a transitional environment on

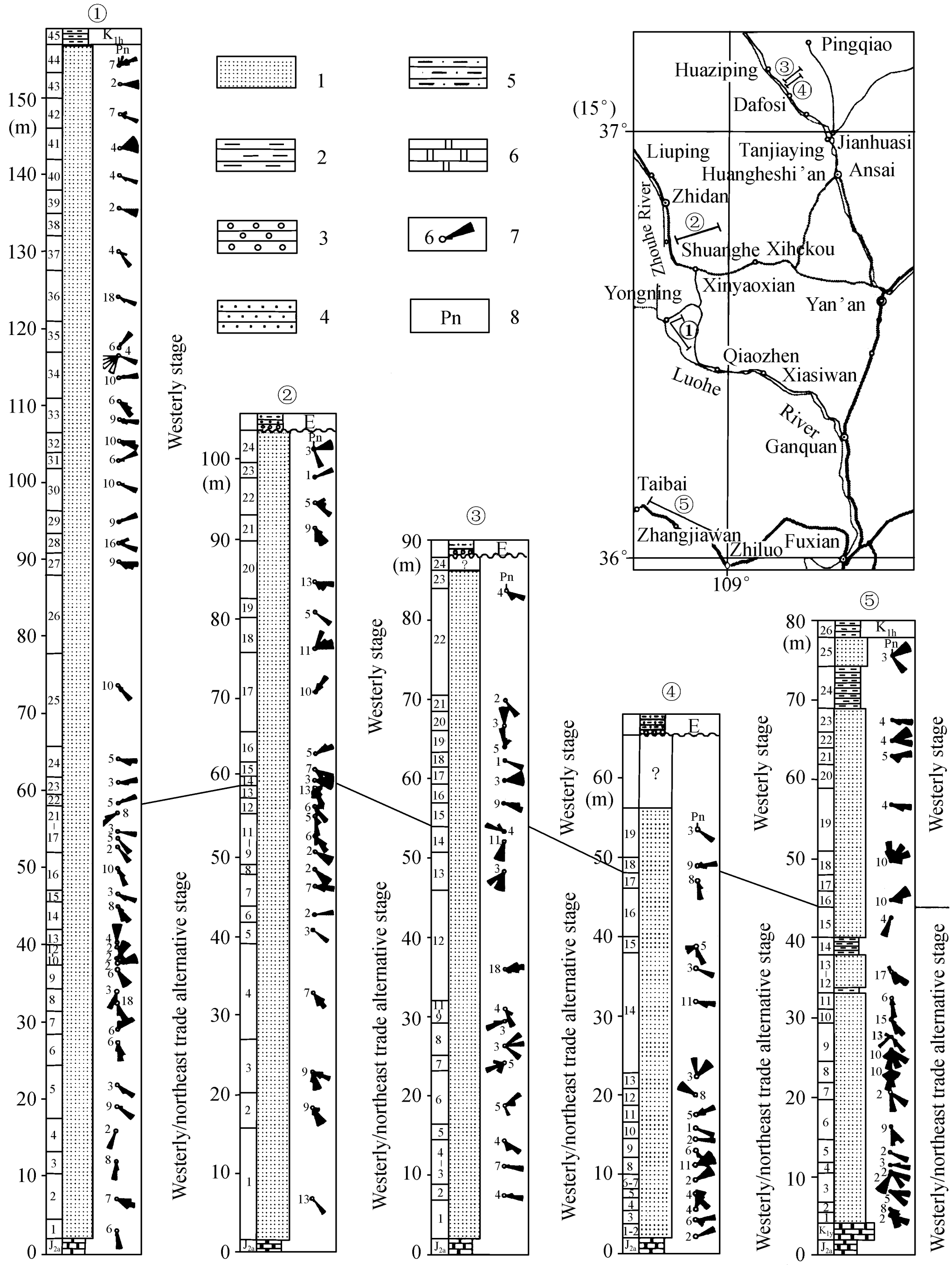

Fig. 2. Rose column of foreset dips of dunes in Early Cretaceous Luohe Formation in Ordos Basin (revised by 15° anticlockwise rotation).

the desert margin.

Above the solid line is the product of westerly belt and below the solid line is the alternative products of northeast trade and westerly belts; the overlying strata are the Early Cretaceous Huanhe-Huachi Formation (K_1h) or Tertiary (E); the underlying strata are the Early Cretaceous Yujun Formation (K_1y) or Middle Jurassic Anding Formation (J_2a).

Luohandong Formation in Fangshan section, Zhengyuan is composed of 25 dune units interbedded with lots of wet interdunes in which mud cracks and calcareous concretions are well developed, being the typical central environment of the desert. All the cross-beddings are dipping in the east (fig.1). Qi et al.[14] have collected about 150 directional data which dip in 80°—90° and 140°—150° dominantly, being similar to our results. The section in Yongning Village, Zhidan County (fig. 2-①) is the nomenclature section of Luohe Formation, which is about 160 m thick and composed of 44 dune cross-bedding units. The eolian sediment of the formation transforms upwards into the fluviolacustrine sediment of Huanhe-Huachi Formation and parallelly unconformed on the silicated dolomite of the Jurassic Anding Formation. It is mostly composed of large tabular-planar cross-bedding units, only a few of which are superimposed by some wedge-planar cross-bedding units, being draa sediments. The superimposed wedge-planar cross-bedding units are the products of small barchans, while the large scale tabular-planar cross-bedding units are the products of transverse draas which, as are superimposed by barchan dunes, are complex draas. Below the 21th horizon, the dip directions are relatively variable, dipping in the east and the southwest dominantly, the cross-beddings of the 3, 4, 8, 21th horizons dip in southwest with some occasions of dipping in the north or south. However above the 22th horizon the cross-beddings dip uniformally in the east with the exception of the upper part of the 34th horizon which is superimposed by 3 small dunes dipping reversely. Sections ②, ③, ④ are similar to section ①, only the upper parts have been eroded and unconformed parallelly by the Tertiary. As section ⑤ is located in the southwest fluvial environment, its bottom contacts with the underlying distal fan conglomerate of Yujun Formation, the top of which transforms into the fluviolacustrine sediments in Huanhe-Huachi Formation. The wet interdunes are well developed, and the 12, 14, 24th horizons of which are muddy silts of wet interdunes with level beddings, small ripple laminae, burrows and mud cracks. Below the 15th horizon, the dips of the cross-bedding are of two main directions as mentioned above, from the 16th horizon above, the dips are relatively uniformally dipping in the east. Based on the judgements above, there are more barchans in the section, such as 8th, 9th, 18th and 25th horizons. According to the varying trends of thickness, it seems that the thickness of Luohe Formation is reducing with the increasing thickness of Yujun Formation. In the southwest, Yujun Formation reaches its greatest thickness with the coarsest grain sizes which are reducing gradually northeastwards, while the thickness of Luohe Formation is increasing northeastwards. From the composition of the sedimentary facies of Luohe Formation, there are more wet interdune and wadi sediments in the southwest which phase out northeastwards. Therefore, it is concluded that the desert center is located in the northeast part of the basin and the desert margin is located in the southwest.

Before determining the wind direction, it should be made clear that: first of all, the extending lines of dunes are not straight, the foresets are curved surfaces, so the data from different parts are certainly different; secondly, the curved surfaces of different types of dunes are different, resulting in the different spreads of vectors; thirdly, the wind directions sometimes have a small angle with dune migrating direction; fourthly, the wind direction obtained from some small dunes are unreliable; fifthly, influenced differently by the Coriolis force and local topography, the wind direction vectors themselve are of certain divergent range. Thus, in this paper, the vectors between north and southeast are combined into the eastern vector group and the vectors between south-southeast and west into the southwestern vector group. The demonstration of the roses indicates that the dips of foresets from the upper part of Luohe Formation to Luohandong Formation are confined in eastern vector group, meaning that the dunes in this period moved eastwards and westerlies were pevailing; while the dips of the foresets in the lower part of the Luohe Formation are sometimes confined in southwestern vector group and sometimes in eastern vector group, implying that the dunes of the period sometimes migrated southwestwards and sometimes eastwards; and westerlies and north easterlies were prevailing alternatively with westerlies dominant.

2 Reconstruction of paleowind belts

Ordos Basin was located in the middle and low latitude of the northern hemisphere (31.2° N) during the Early Cretaceous[25], just crossing the subtropical high pressure zone of that time[5—7, 9—11]. As the topography in that time was relatively even which had less influence on the pattern of the general circulation of the atmosphere, the wind direction change trend is just coincident with the ideal model of wind belts on the earth (fig. 3). Based on the model, it is suggested that the eastern vector group must have resulted from westerly belt, while the southwestern vector group must have been produced by northeast trade belt. Further analysis shows that the early stage of this desert was in the alternating period of westerlies and northeast trades, and the late stage was in the period of westerlies. Thus, the wind system of them must be planetary wind system. The study on the Late Cretaceous wind directions in Sichuan Basin which is in the south of Ordos Basin also suggests the same conclusion[26, 27]. The only exception is that the event was later than that of Ordos Basin, indicating that the subtropical high pressure zone together with westerly belt had been drifting southwards. From the 5 sections shown in fig. 2, the wind directions are generally in the east and southwest, which are compatible with the modern dune’s migrating directions in this basin[17]. The difference is that, because of the interaction of the Tibetan Plateau, the modern dunes

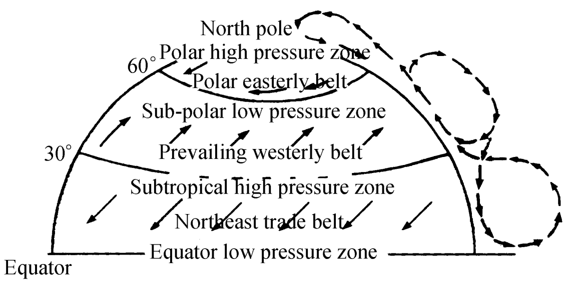

Fig. 3. Wind belt distribution in the northern hemisphere (after Gao Guodong et al., 1988).

are located further north than they should be. In addition, this compatibility does not exclude the influences from the land-oceanic thermal gradient and the paleomonsoon circulations.

3 Interpretation of generation of wind direction changes

The climatological study[28] shows that the replacements of wind belts in a region are checked by the movement of general circulation zones of the atmosphere, and the movements of the circulation zones are controlled by the changes of equator-pole temperature gradients. Basically, the subtropical high pressure zones may drift north and southwards with the fluctuations of the temperature gradients, causing the north and southwards driftings of the trade and westerly belts. The drifting may be annual changes by seasonal climatic fluctuation and may also be perennial changes by long climatic fluctuation. According to the durations of dunes mentioned above, the representation of the records in the desert must be the long periodic perennial changes.

By the wind direction change trends analysed above, during the early stage of the desert, the subtropical high pressure zone has drifted sometimes northwards and sometimes southwards, making the northeast trade belt and the westerly belt beside the subtropical high pressure zone advance at one time and retreat the next, resulting in the frequent alternations of westerlies and northeast trades. But during the late stage of the desert, the subtropical high pressure zone might have drifted southwards and the westerly belt might have stayed on the desert for a long period, making the westerlies dominant. The Bigarella's interpretation to the wind belt replacement in the Sahara desert since the Pleistocene is the same as we used[28]. Besides, Dong Guanrong's interpretation that the changes of the desertification and bioclimatic belt in Horqin sandy land are concordant with global temperature fluctuations caused by the gracial and intergracial fluctuations[29] also provides powerful collateral evidence for our interpretation.

The generations of the subtropical high pressure zone and wind belt driftings have no more than two posibilities: i. e. relative drifting and absolute drifting of the general circulation zones of the atmosphere. The relative drifting means that continental block is moving while the zones of the circulation are keeping still. The result of paleomagnetic study suggests that the tectonics was under a relatively stable period and the northern China block did not move north or southwards for a great distance, but did a certain clockwise rotation. The interpretation of the diachronous phenomenon from north to south in the Cretaceous deserts of the middle eastern China by Jiang Xinsheng et al. has suggested a relative drifting[5,6]. It is interpreted that the basin vacillated north and southwards at first and then rotated clockwise, which made the subtropical high pressure zone move southwards relatively. This has been evidenced not only by paleomagnetism[21—25], but also by the migration of flora provinces, deposition minerals and sedimentary facies distribution[30]. The absolute drifting is that the continental block stands still but the zones of the general circulation of the atmosphere move. It may be the north and southwards vacillation possibly caused by the temperature gradient changes on the earth coupled with the global temperature fluctuations. Judging by the seasonal drifting of modern subtropical high pressure zone, it seems completely possible, but no evidence has been found. It is estimated that there was a catathermal event in late period which made the subtropical high pressure zone drift southwards completely, being similar to the southwards migration of the Sahara desert in North Africa during the Pleistocene. However, this interpretation is contradicted by conventional ideas on the Cretaceous climate which has long been described as a "uniform warm" and low temperature gradient period. Some one has doubted it[5, 6] and even found evidence for the temperature fluctuations during the Cretaceous[31].

4 Climatic significance

It is well known that the existence of the Tibetan Plateau is the key factor for the pattern of the general circulation of the atmosphere in eastern Asia. The special thermodynamics, obstruction and bifurcation of the plateau lead to the establishment of the eastern Asian monsoon systems[28]. However, the formed knowledge about the wind belt and circulation pattern before the uplift of the high plateau only remains at the stage of modeling and deducing and no measured data have been reported. The reconstruction of the wind belts above gives further evidence for the existence of the planetary wind system in eastern Asia.

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