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Optical dating of Holocene dune sands from the Hulun Buir Desert, northeastern China

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A HOLOCENE RESEARCH REPORT

Abstract: Aeolian deposits from the Hulun Buir Desert of northeastern China are studied with optically stimulated luminescence dating methods to establish the chronology of dune building phases and climatic changes since the last deglaciation. Our results indicate that wet climate, marked by dune stabilization and soil development in the Hulun Buir Desert, commenced at ~11 ka ago, and this early episode of dune stabilization lasted until ~4.4 ka ago. This optimum climate between ~11 and ~4.4 ka ago is mostly the response to the strengthened monsoon circulation and increased precipitation in the Northern Hemisphere. The environment generally became arid after ~4.4 ka ago, but the dry climate was interrupted by three phases of weak soil development occurring at ~1.8–1.4, ~1.2–1.0 and ~0.84–0.5 ka ago, respectively. Such short events of dune stabilization were associated with the warm and humid climate in historical time. However, the present dune mobilization in the Hulun Buir Desert is mainly the result of poor land-use practices (land cultivation and overgrazing) since about 300 years ago.

Key words: Optical dating, Holocene, Hulun Buir Desert, dune activity, China, monsoon.

Introduction

Aeolian and aeolian-related deposits are important for palaeoclimatic and palaeoenvironmental reconstructions in arid and semi-arid regions (eg, Rognon, 1987; Lancaster, 1989, 1990; Petit-Maire and Page, 1992; Nanson *et al.*, 1992; Stokes *et al.*, 1997; Goudie, 1999; O'Connor and Thomas, 1999; Thomas *et al.*, 2000). In China, active sand dunes mainly occur in the northwest inland basins (eg, the Taklimakan Desert), whereas deserts dominated by semi-stabilized sand dunes are mainly distributed in the northeastern semi-arid and subhumid regions (eg, Hulun Buir Desert). Recent studies indicate that the southern limits of deserts in northeastern China have shifted in space and time, in response to changes in the east Asian monsoonal circulations (Sun *et al.*, 1998, 1999). Thus, northeastern China is one of the key regions in which to study the history of past environmental changes.

The alternations of sand accumulation and soil formation of these aeolian deposits are regarded as evidence for desert expansion and contraction during the Quaternary. Low organic carbon content, and possible carbon contamination from the roots of modern vegetation, make it difficult for accurate radiocarbon dating. In spite of this, there have been few papers concerned with palaeoenvironmental reconstruction in deserts in the Holocene, using radiocarbon dating (eg, Wang, 1992; Li and Dong, 1998). Only in recent years has optically stimulated luminescence (OSL) dating been carried out on the fossil sand dunes of northeastern China (Li *et al.*, 2002; Sun *et al.*, 2006). The application of OSL dating to aeolian sequences heralded a new phase of aeolian geochronology (Huntley *et al.*, 1985; Stokes and Gaylord, 1993; Stokes *et al.*, 1997; Murray and Olley, 2002; Goble *et al.*, 2004). The single-aliquot regenerative-dose (SAR) technique has improved the accuracy and precision of OSL dating (Murray and Wintle, 2000). In this paper, we focus on discussing Holocene climate change as derived from systematic OSL dating of dune sediments in the Hulun Buir Desert.

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Geological setting

The Hulun Buir Desert is located in northeastern China (47°49′–49°35′N, 117°16′–119°32′E), and it currently has vegetation cover of up to 50%. Stabilized and semi-stabilized sand dunes are distributed mainly in the northern and southern parts of the desert (Figure 1), whereas the other areas are dominated by grassland. The dominant dune types of this desert are transverse dunes. These dunes form under winds that

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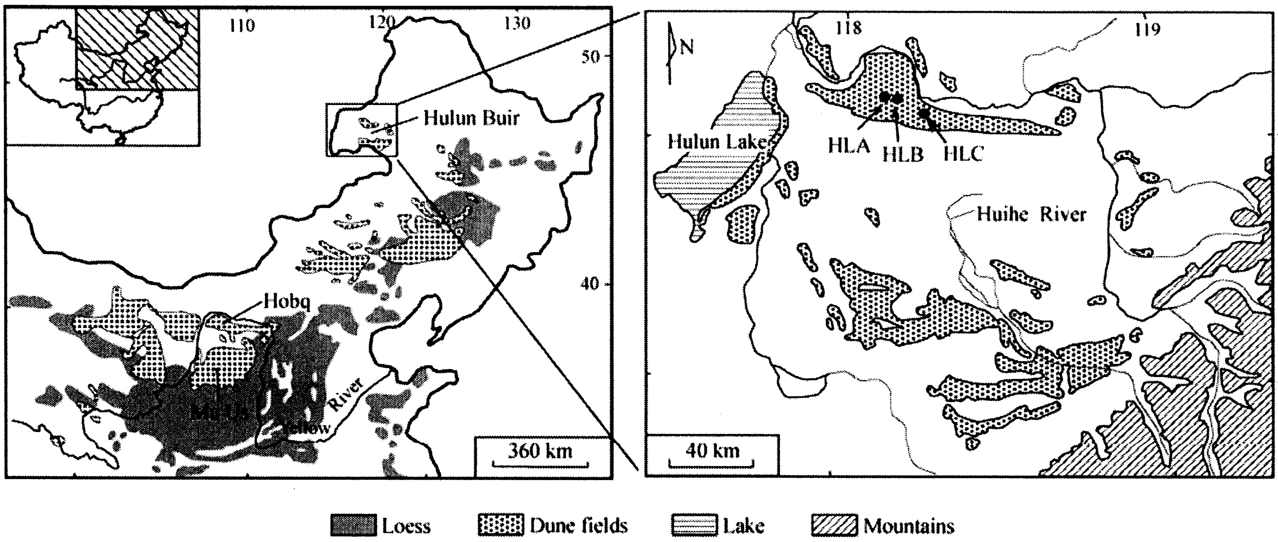

Figure 1 Map showing the deserts and the sites mentioned in the text

blow from one direction, and they also are known as barchans. The height of the dunes mostly varies from 5 to 15 m.

The mean annual precipitation in the study area ranges from 250 to 350 mm, and the monsoonal rainfall mainly occurs in the months of July to September. The mean annual temperature varies from -2 to 0°C. According to the meteorological records, the average frequency of strong winds with velocity of above 17 m/s ranges from 20 to 40 times per year; this mainly occurs in the dry and windy Spring season (Wang, 1990). The mean annual dust storm days last usually less than 2 days and are the shortest among the deserts in China. However, vegetation cover has been partially destroyed through cultivation and/or overgrazing, and this leads to increased sand mobility and reworking of the stabilized sand dunes.

Materials and methods

In this study, three sections (HLA, HLB and HLC, Figure 1) from the interior of the northern dune fields of the Hulun Buir Desert were sampled for OSL dating. The aeolian sequences of the studied sections consist of alternating deposits of dune sands and dark brown sandy soils (Figure 2). For all the three sections, the lowest palaeosol was most developed and characterized by a dark brown color (7.5 YR, 3/3), whereas the other soils were less developed and were dull brown (7.5 YR, 5/3). There were sedimentary hiatuses in sections HLA and HLB. For section HLC, the top layer is a relict soil, implying the deposits above this soil were eroded (Figure 2). In all sections, outcrops at the bottom of the sections do not represent the full depths of the sand beds underlying the soils; these are usually quite thick, hence only the upper part is studied (Figure 2). We collected 20 OSL samples from the three sections. Among them, seven are from section HLA, ten are from HLB and three are from HLC. Detailed sampling positions of the 20 samples are given in Figure 2 and Table 1.

All OSL samples were obtained by hammering aluminum cans into cleaned vertical sections. The sample cans were covered with a lid immediately after taking them from the section, then sealed inside plastic bags with tape to ensure that the sediment retained its natural water content. In the laboratory, the material at each end of the can was scraped away and used for dose rate measurements. Quartz grains were prepared following procedures of sieving, heavy liquid separation and HF etching in subdued red safe light conditions. Raw samples were treated first with 20% H_2O_2 and 10% HCl to remove organic materials and carbonates. Grains between 150 and 180 μm were selected by mechanical dry sieving. Grains of density between 2.62 and 2.70 g/cm^3 were separated using sodium polytungstate heavy liquid. The separated grains

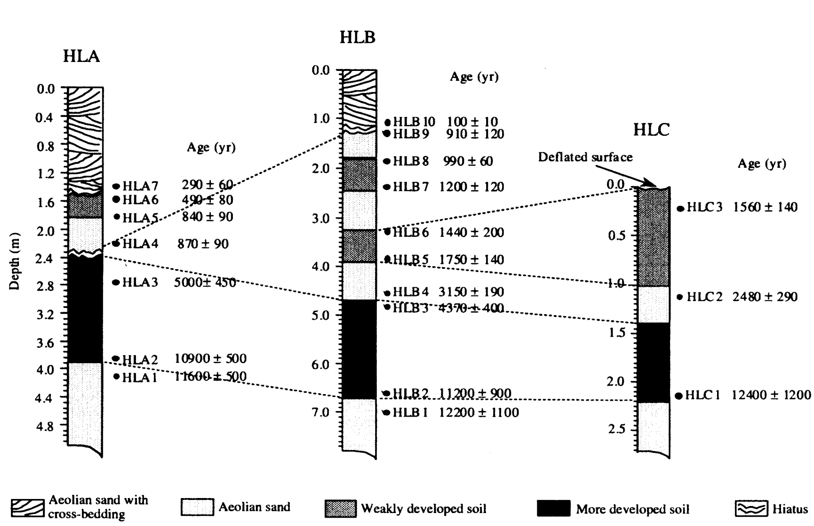

Figure 2 Stratigraphy, sampling depths and the OSL ages for the three sections

Table 1 Equivalent dose, dose rate and OSL ages for samples from the Hulun Buir Desert

Site	Sample	Depth (m)	Alpha count rate[a]	K content (%)	Water content[b] (%)	Cosmic ray[c] (Gy/1000 yr)	Equivalent dose (Gy)	Dose rate (Gy/1000 yr)	OSL age (years)
HLA	HLA 7	1.20	2.92	1.91±0.07	0.7	0.25	0.73±0.15	2.51±0.09	290±60
	HLC 6	1.55	3.38	1.97±0.08	0.9	0.25	1.28±0.20	2.62±0.10	490±80
	HLC 5	1.70	3.36	1.95±0.08	1.2	0.23	2.16±0.22	2.58±0.10	840±90
	HLC 4	2.30	3.47	1.96±0.08	1.7	0.21	2.22±0.21	2.54±0.10	870±90
	HLC 3	3.15	4.58	1.93±0.07	3.7	0.20	13.04±1.08	2.62±0.10	5000±450
	HLC 2	3.86	3.56	1.89±0.07	3.1	0.18	26.53±0.60	2.42±0.09	10900±500
	HLC1	4.15	2.81	1.80±0.06	2.0	0.16	26.32±0.51	2.25±0.09	11700±500
HLB	HLB10	1.05	2.68	1.80±0.09	2.0	0.25	0.24±0.03	2.33±0.10	100±10
	HLB 9	1.25	2.66	1.83±0.08	3.0	0.25	2.06±0.25	2.27±0.10	910±120
	HLB 8	1.85	2.74	1.83±0.09	3.2	0.23	2.25±0.11	2.35±0.10	990±60
	HLB 7	2.34	2.74	1.86±0.08	1.9	0.21	2.83±0.24	2.35±0.10	1200±120
	HLB 6	3.30	2.81	1.85±0.09	2.6	0.20	3.34±0.44	2.32±0.10	1440±200
	HLB 5	3.82	2.75	1.79±0.07	2.5	0.18	3.96±0.26	2.27±0.10	1750±140
	HLB 4	4.50	2.72	1.91±0.07	2.1	0.13	7.50±0.33	2.40±0.11	3150±190
	HLB 3	4.80	4.89	1.88±0.07	5.0	0.12	11.26±0.88	2.58±0.11	4370±400
	HLB 2	6.60	4.10	1.88±0.08	4.2	0.06	27.81±2.02	2.49±0.10	11200±900
	HLB1	7.00	2.63	1.94±0.06	3.5	0.05	28.69±2.29	2.35±0.10	12200±1100
HLC	HLC 3	0.15	2.39	2.31±0.12	1.3	0.29	4.53±0.58	2.90±0.10	1560±140
	HLC 2	1.12	2.79	2.31±0.12	1.9	0.25	7.2±0.8	2.91±0.12	2480±290
	HLC 1	2.15	4.14	2.39±0.13	6.5	0.21	36.9±3.2	2.97±0.12	12400±1200

[a]The alpha counting rate is for a 42-mm-diameter ZnS screen and is given in units of counts per kilosecond.
[b]The error for the water content (expressed as (wt. water)/(wt. dry sediment)) is estimated at ±20%.
[c]The error for the cosmic rays dose rate is estimated at ±0.02 Gy/1000 yr.

were treated with 40% hydrofluoric acid for 2 h to destroy any remaining feldspar. Separated quartz grains were mounted on 10 mm diameter aluminum discs with 'Silkospay' silicon oil for measurement. The purity of quartz grains was tested by monitoring for the presence of feldspar by measuring the infrared stimulated luminescence and the 110°C TL peak (Li *et al.*, 2002).

OSL measurements were made in the Luminescence Dating Laboratory of The University of Hong Kong using an automated Risø TL/OSL reader equipped with excitation units producing blue/green light (420–560 nm) (Markey *et al.*, 1997). The OSL signal is detected through two 3 mm Hoya U-340 filters. Irradiation was carried out using a $^{90}Sr/^{90}Y$ beta source built into the reader with a dose rate of 0.040 Gy/s to quartz on aluminum discs. The equivalent doses (D_e) were determined by the single aliquot regeneration (SAR) protocol (Murray and Wintle, 2000) with preheating at 260°C for 10 seconds and a cut heat temperature of 220°C. The OSL signals, L_n and L_x, integrated from the first 2 seconds and subtracting the equivalent average of OSL signals in the last 10 seconds, were taken as the OSL intensity used for D_e value determination. Sensitivity monitoring was achieved by measuring the OSL signal, T_n and T_x, created by a test dose of typically 4.0 Gy. The D_e values were calculated using the corrected OSL intensities L_n/T_n and L_x/T_x. All samples were subjected to tests for recycling and dose recovery; aliquots with a recycling ratio falling out the range of 1.0±0.1 and recovering a dose more than 10% away from the delivered dose were not used in D_e calculation.

The environmental dose rate was measured using a variety of techniques. Thick source alpha counting (TSAC) was used to measure contributions from the U and Th decay chains. The alpha count rates were converted into alpha, beta and gamma dose rates according to Aitken (1985). K content was measured by flame photometry. Water content was the ratio of water weight to the dried sample weight, obtained from the sample weights before and after drying at 105°C in an oven (Table 1). The cosmic ray contribution to the dose rate was calculated from the burial depth and the altitude of the samples (Prescott and Hutton, 1994).

Results

Optical ages of samples from the Hulun Buir Desert are shown in Table 1. The calculated ages fall within the range 12.4±1.2 ka to 100±10 years ago, with the errors associated with individual ages ranging from 6% to 14%. At each site, ages increase with depth. The existence of several soils indicates that this area is characterized by multiple periods of dune stabilization and sand mobilization. The eroded top surface in section HLC clearly implies that the pre-existing dune deposit above the surface has been deflated. Based on the pedostratigraphy and the OSL ages, the three sections can be correlated as indicated in Figure 2.

The observed stratigraphic breaks in sections HLA and HLB are also supported by the ages obtained. For example, the dune sands above the uppermost break in section HLB yields an age of 100±10 years (HLB10), whereas below the break sample HLB9 gives an age of 910±120 years (Figure 2). There is OSL evidence of reworking of dune sand at the top of section HLA. The distribution of aliquot equivalent doses for sample HLA7 shows a different pattern from that of the underlying sample HLA6 (Figure 3). Aliquots with D_e values significantly greater than the average in sample HLA7 indicate that they contain insufficiently bleached grains that are likely to be the result of reworking (Li, 1994, 2001); in contract, a uniform distribution of D_e values was observed for sample HLA6.

Discussion

The determination of optical ages from the three sections allows the construction of a composite record of the multiple

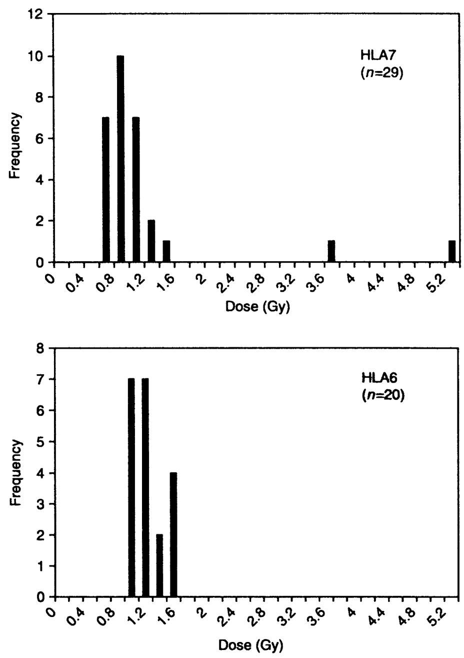

Figure 3 Histograms of D_e distributions for samples HLA7 and HLA6

phases of dune stabilization marked by soil development (Figure 4a).

Previous studies indicate that desert expansions occurred in China during the last glacial maximum (Sun *et al.*, 1998). However, by the end of the Younger Dryas and the beginning of the Holocene, fluvial-lacustrine deposits (Xiao *et al.*, 2002) and stabilized sand dunes occurred in the deserts of northeastern China, implying more humid conditions during the Holocene (Li *et al.*, 2002; Sun *et al.*, 2006). Based on our OSL dating results, the beginning of dune stabilization and soil development in the Hulun Buir Desert occurred at ~11 ka ago. As shown in Figure 4, this early episode of dune stabilization during the Holocene lasted until ~4.4 ka. In addition, at each of the three sections, the lowest soil has the highest organic matter content and the darkest colour of all the Holocene soils. Thus, it is the most developed soil and indicates that it was formed during the optimum climate of the Holocene in this region.

Changes in the orbital parameters of the Earth provide an explanation for the observed optimum climate occurring

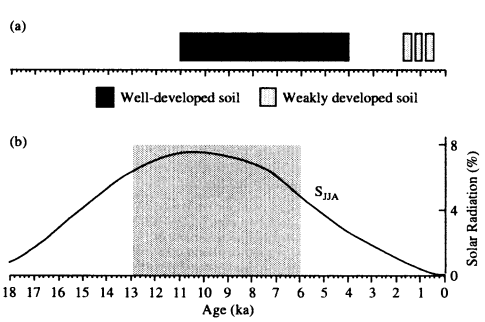

Figure 4 A composite record of the multiple phases of dune stabilization marked by soil development based on OSL ages given in Figure 2 (a) and its correlation with (b) the Northern Hemisphere solar radiation in June–August (S_{JJA}) (Kutzbach and Street-Perrott, 1985). Shaded area indicates the high values in summer solar radiation *c.* 13–6 ka

c. 11–4.4 ka in the Hulun Buir Desert. Previous studies indicated that the orbitally induced solar radiation was highest from 13 to 6 ka ago (Kutzbach and Street-Perrott, 1985, Figure 4b). Experiments with atmospheric general circulation models (AGCMs) for the radiation conditions around 9 ka have confirmed the enhanced monsoonal response to changed orbital forcing and indicated substantial increases in precipitation in the Northern Hemisphere (Kutzbach, 1981). Thus, the observed climatic optimum that occurred *c.* 11–4.4 ka, as marked by dune stabilization and soil development in the Hulun Buir Desert (Figure 4a), is the result of the intensified east Asian summer monsoon, which has played an important role in the transport of humid air masses from the low-latitude western Pacific to the Hulun Buir Desert.

The sections in Hulun Buir Desert indicate that the dune stabilization of the Holocene Optimum ended around ~4.4 ka ago, and multiple periods of dune mobilization occurred during the late Holocene. Although there are still intercalated soils in the sections after ~2 ka ago, they are weakly developed compared with the soil developed during the Holocene Optimum. The existence of the several aeolian sand beds and the interbedded weak soils indicates that the climate after ~4.4 ka ago generally became arid and unstable. The OSL ages of the weak soils suggest that three phases of dune stabilization occurred during the late Holocene, at *c.* ~1.8–1.4, ~1.2–1.0 and ~0.84–0.5 ka ago (Figure 5c); these are based on OSL ages at the top and bottom of the weak soils at HLA and HLB, with confirmation of the older period at HLC. It is of particular interest that these soils were formed over as little time as 100 years.

In order to study the relationship between climate change and late-Holocene soil development, we have compared the composite soil development phases with climatic records for China during the last 1.8 ka (Figure 5a and b). First, although China has abundant historical documents with the earliest records going back as far as 5–3 ka ago, there are relatively few items of documentary data for the early period. However, based on the compiled historical lake data base, Fang (1993) reconstructed a humidity index for China during the past 1.4 ka (Figure 5a). Second, Tan (2003) reconstructed a stalagmite record of temperature during the warm season for the last 1.8 ka (Figure 5b). These climatic records provide the basis for comparison of the episodic dune stabilization with climatic change. Figure 5 indicates that the three phases of dune stabilization during the last 1.8 ka (Figure 5c) broadly correlate with the warm and humid climate episodes, suggesting that climate change plays an important role in controlling dune activity in the Hulun Buir Desert. We infer that these periods of dune stabilization during the last 1.8 ka reflect the variations in solar radiation related to suborbital changes on the century scale through its control of monsoon activity.

It is worth noting that the climate becomes both warm and more humid again in China after ~300 years ago (Figure 5). However, modern soils are not observed in the Hulun Buir Desert. Instead, OSL ages indicate that the basal ages for the modern dunes are 290±60 yr (HLA7), and 100±60 yr (HLB10), respectively (Figure 2), suggesting dune mobilization during the past 300 years. Actually, this latest dune mobilization is may be due to poor land-use practices. Compared with the early land cultivation and human migration in the Mu Us Desert (Sun, 2000), cultivation in the Hulun Buir Desert happened much later. Historical documents indicate that since AD 1697 (in the late Qing Dynasty of China), people from central China migrated to

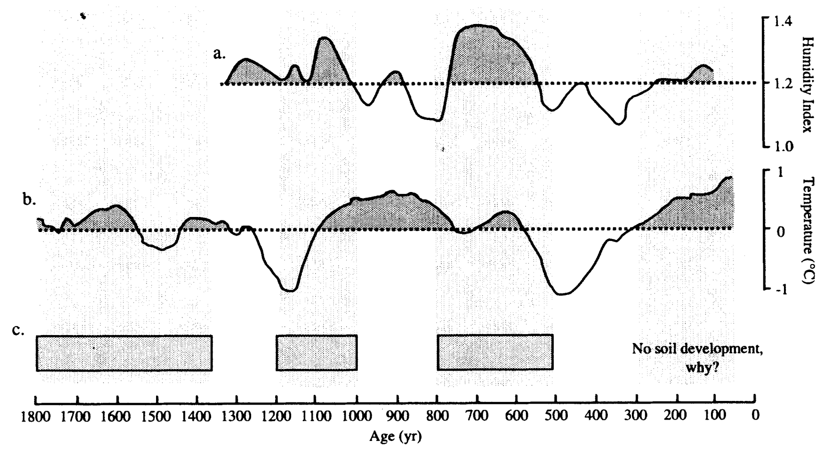

Figure 5 Correlation of (a) the humidity index for eastern China since 1.4 ka ago (Fang, 1993) and (b) the temperature changes retrieved from stalagmite records in China since 1.8 ka ago (Tan *et al.*, 2003),with (c) the three phases of weak soil development in the Hulun Buir Desert. It is worth noting that warm and humid climate is responsible for the soil development and dune stabilization (both of the dashed lines correspond to the overall mean of the reconstructed series)

the Hulun Buir Desert and cultivated lands in this region. Such activities, together with overgrazing, destroyed the natural vegetation cover and led to dune mobilization at many sites in the Hulun Buir Desert. Even now, we can find cultivated lands in the Hulun Buir Desert (Figure 6a), where the potential for sand reworking is quite high; also sites where the palaeosol developed during the Holocene optimum has been eroded, leading to the reworking of the buried dune sands (Figure 6b).

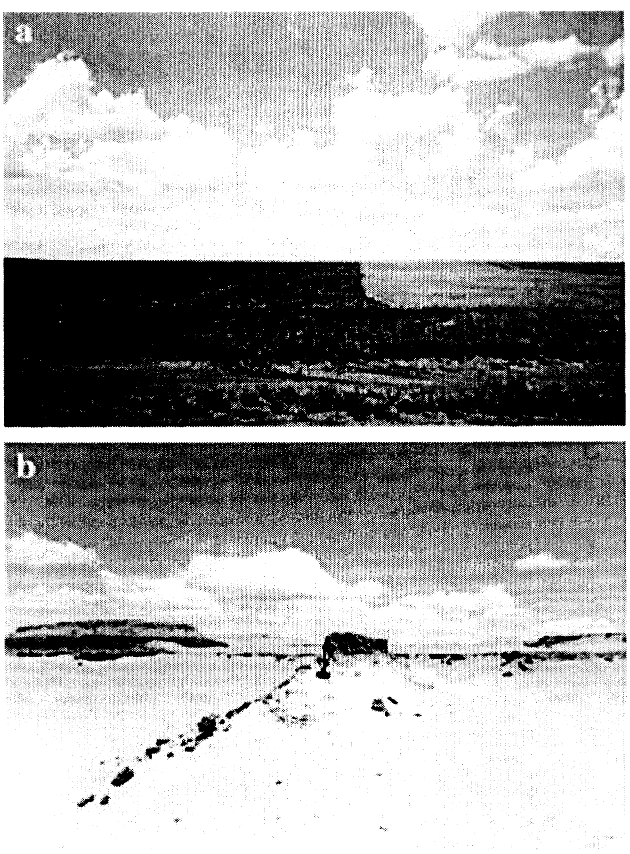

Figure 6 (a) Cultivated lands in the Hulun Buir Desert, and (b)

Conclusion

Optical dating can be used to obtain the ages of dune activity and soil formations in the Hulun Buir Desert. Our results indicate that the Holocene Optimum, marked by dune stabilization and soil development that occurred between ~11 and ~4.4 ka ago, is the response to the enhanced east Asian summer monsoon controlled by the increased orbitally induced solar radiation *c.* 13 to 6 ka ago. The climate generally became arid after 4.4 ka ago, but the dry climate was interrupted by three phases of weak soil development and dune stabilization occurring at ~1.8–1.4, ~1.2–1.0 and ~0.84–0.5 ka ago. Such events of dune stabilization were associated with the warm and humid climate in historical time. However, during the past 300 years, human impact has had a great effect on the ecosystem of the Hulun Buir Desert. Human migration and the increasing agricultural economy have destroyed the vegetation cover, resulting in dune mobilization at many sites in the Hulun Buir Desert. Our view of the importance of land-use practice suggests that, in the fragile ecological system where a great quantity of sand is available for reworking and high wind energy is concentrated, any unreasonable human activities will greatly accelerate sand mobilization processes.

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