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Abstract

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Keywords

central, changes, us, holocene, sala, sediments, valley, dating, river, luminescence, revealed, mongolia, environmental, inner, CAS

Disciplines

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Holocene environmental changes in central Inner Mongolia revealed by luminescence dating of sediments from the Sala Us River valley

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Abstract

Luminescence dating of the fluvial and lacustrine sediments from the Sala Us River valley at the south edge of the Mu Us Desert, central Inner Mongolia, is reported. The studying region lies in the northwestern marginal zone of the east Asian summer monsoon and is sensitive to climate changes. The dating results combined with environmental proxies indicate that the Holocene climate Optimum period, took place from 8.5 to 5 ka ago and was marked by lake development. After ~ 5 ka ago, the region became arid, as inferred by lake regression and fluvial activity. Deposition of fluvial sediments lasted from ~5 ka to ~2 ka ago. At about 2 ka ago, incision of the Sala Us River was initiated into the underlying sediments, with a down cutting rate of ~3-4 cm/year. Since 2 ka ago, human activities also played an important role in causing environmental change in the region.

Keywords: Mu Us Desert, Sala Us River, luminescence dating, Holocene, palaeoenvironment, Asia Monsoon

1 Introduction

The semi-arid and arid regions are of interest for palaeoenvironmental and palaeoclimatic studies because the environments in these regions are sensitive to climate changes and vulnerable to human impact (Sun and Ding, 1998; Sun et al., 1999; D'Arrigo et al., 2000; Thomas et al., 2000; Li et al., 2002; Feng et al., 2006; Li and Sun, 2006). The Mu Us Desert locates in northern China, its climate is largely controlled by the east Asian monsoon systems, which are caused by the differential heating between the largest continent of Eurasia and the Pacific Ocean. In winter, the strongly cooling over the continent gives rise to the formation of a low-level cold high pressure cell over the Siberian region. The southwards cold air outbreaks associated with the Siberian High usually cause cold and dry northwesterly winds-called east Asian winter monsoon (Chen et al., 1991). In summer, the high pressure cell over the Pacific couples with the Indian Low leads to prevailing southeast summer monsoon. Because the Mu Us Desert is just near the northern limit of the east Asian monsoon (Fig. 1), its ecosystem is highly sensitive to palaeoclimatic changes. Previous studies revealed that the Mu Us Desert has experienced cycles of expansion and retreat, in response to changes in the East Asian monsoonal circulations, characterized by expansions during winter monsoon dominated glacial stages and contractions during summer monsoon dominated interglacial periods. In this sense, the deposits in this region are ideal for studying past environmental changes in central China and its response to the east Asian monsoonal circulations (Sun et al., 1998; Sun et al., 1999). Moreover, there have been episodes of human migrations and agricultural activities over the last 5000 years (Wang, 1985; Sun, 2000; Sun et al., 2006), providing excellent example for studying the effects of human impact and climatic changes on the fragile ecosystem of this region.

In order to investigate the environmental changes in these regions, it is imperative to obtain a chronological framework and have temporal records of climatic proxies. The application of radiocarbon dating in desert regions is hampered mainly due to lack of organic content (Head et al., 1989) and its age limit (<50,000 years). Dating of sediments from arid regions is better achieved using optically stimulated luminescence (OSL) techniques (Aitken, 1998), in which the time elapsed since the last exposure of the mineral grains to sunlight is determined. Over the last decade, the

development of the single-aliquot regenerative-dose (SAR) technique (Murray and Wintle, 2000) has enabled the wide application of OSL dating of sediments. Particularly, OSL dating has been successfully applied to reconstruct the timing of past environmental changes in arid and semi-arid regions in north China in the last few years (Li et al., 2002; Li and Sun, 2006; Sun et al., 2006; Yang et al., 2006; Li et al., 2007; Lu et al., 2007; Zhou et al., 2009). Isochron dating using different grain sizes of potassium rich (K) feldspar has been developed in recent years (Li et al. 2008b). This technique determines the equivalent dose of different grain sizes of K-feldspar with infrared stimulated luminescence (IRSL). It can overcome both anomalous fading of K-feldspars and the effects of past changes in the environmental dose rate (Li et al. 2008a).

In recent years, a variety of climatic proxies including sedimentological, physical, geochemical, biological, and mineralogical parameters have been used in palaeoenvironmental reconstructions for Chinese eolian deposits (e.g., Liu, 1985; Ding et al., 1994; Heller and Liu, 1984; Chen et al., 1999; Ji et al., 2004). Among them, the organic carbon content and the particle sizes are commonly used proxies. In this study, we report the chronology of sediments in the southern marginal Mu Us Desert. Combined with the variations of climatic proxies, we aim to reconstruct the environmental changes in the southern Mu Us Desert and discuss the regional scale palaeoenvironmental evolutions.

2 The Study area

The Mu Us Desert (37°28'-39°23' N and 106°10'-110°30' E) is located on the Southeast Ordos Plateau adjacent to the Loess Plateau and situated in the zone affected by the Asian monsoon (Fig. 1). The mean annual temperature in the Mu Us Desert ranges from 5.5 to 8.0°C and the mean annual precipitation ranges from ~200 mm in the northwest to ~450 mm in the southeast, with more than 60% of the annual precipitation being received from July to September (Members of Loess Plateau Investigation Group, 1991). Sand dunes in the Mu Us Desert are dominated by stabilized and semi-stabilized sand dunes of barchans chains with heights of up to 20 meters. Previous studies suggested that the modern active sand dunes represent reactivation and reworking of sands deposited during the last glacial maximum (LGM) (Sun, 2000).

The Sala Us River flows across the southeast margin of the Mu Us Desert (Fig. 2). The incision of the river created many valleys up to 1000 m wide and 60-80 m deep. Thick Quaternary sediment strata consisting of interbedded eolian, fluvial and lacustrine deposits, the so-called Sjara Osso-Gol Formation, are well exposed along both banks of the river (Jia, 1950). The Sala Us River area is also an important archaeological site in Northern China where the Holocene Optimum Yangshao Culture, the last glacial to interglacial Ordos Culture and Sala Us vertebrate fossils were discovered (Licent et al., 1927; Teilhard De Chardin and Young, 1930; Teilhard De Chardin, 1941). Therefore, this region is also important for discussing the linkage between human activities and palaeoenvironmental evolutions.

A well known exposure of the Formation is located at Dagouwan site (Fig. 2), where it is 59.7 m thick. It is the most complete and thickest section in the region studied. The Holocene lacustrine and fluvial sediments at this site can be correlated with other exposures along the Sala Us River (Li et al., 1998; Dong et al., 1999; Li et al., 2000; Sun, 2000). Previous chronologies of the Holocene sediments in this region were mainly based on conventional radiocarbon dating (Li et al., 1984; Dong et al., 1998, 1999) and TL dating (Zheng, 1991; Li et al., 1993; Li and Dong, 1998). However, the target material used in radiocarbon dating, mainly bulk organic carbon, was inherently unreliable. Also, the TL signal might suffer from insufficient bleaching (Aitken 1998). Therefore, some of these age data could be inaccurate and a revision of the existing chronology needs is desirable.

3 Stratigraphy

A general description of the whole section at the Dagouwan site has been given by Sun (2000). However, the detail chronology and palaeoenvironmental changes during the Holocene have not been well studied, therefore, this study will focus on the uppermost Holocene deposits with a thickness of 4.8m (Fig. 3). These deposits can be further subdivided into three parts: a lower part consisting of yellowish sands showing well developed cross-bedding, previous studies suggested an eolian origin, its thickness can be up to 7 m; a middle layer consists of grey lacustrine silt, occasionally containing small shells, its thickness is 1.9 m; and an upper part of fluvial sandy silt with horizontal bedding, its

thickness is 1.35 m. The top of the section is currently covered by active and semi-stabilized barchan chains of the Mu Us Desert.

4 Methods

4.1 OSL dating

A total of 10 OSL samples were collected from three units in the section studied (Fig. 3). Steel cylinders or aluminum cans with 50 mm in diameter and 30 cm in length were pushed or hammered into a freshly cleaned vertical section of the profile and immediately covered with a lid. In laboratory, the two ends of the samples in the cylinders were first removed and collected for estimation of environmental dose rate. The samples were then treated with H_2O_2 and HCl to remove organic materials and carbonates, respectively. After that, different grain size fractions, 90-125, 125-150, 150-180, 180-212 and 212-250 μm , were obtained by dry sieving. Quartz grains of 150-180 μm fraction were used for OSL dating. Feldspar in all of the grain sizes were used for IRSL isochron dating. The quartz and K-feldspar grains were then separated using heavy liquid with densities of 2.62-2.75 g/cm^3 and $<2.58 \text{ g}/\text{cm}^3$, respectively. The separated quartz grains in the density between 2.62 to 2.75 g/cm^3 were treated with 40% HF for 2 hours to remove any remaining feldspar. For K-feldspars grains (density less than 2.58 g/cm^3), etching was carried out using 10% HF for 40 minutes. The purity of the quartz grains was tested by monitoring the infrared stimulated luminescence (IRSL) and measuring the 110°C TL peak (Li et al., 2002; Duller, 2003). Pure quartz grains were obtained for the studying samples. All sample preparation procedures were operated under subdued red to orange light ($>590 \text{ nm}$). The separated mineral grains were mounted on 9.8-mm-diameter aluminum discs with Silkospray silicone oil for measurement.

All OSL and IRSL measurements were performed on an automated Risø TL-DA-12 reader equipped with green light filtered broad-band lamp (Bøtter-Jensen and Duller, 1992) and IR diodes (Markey et al., 1997). The OSL signals from quartz were detected through U-340 filters. The IRSL

signals from K-feldspar were detected through a Schott BG-39 filter combined with a Corning 7-59 filter. Irradiation was carried out using $^{90}\text{Sr}/^{90}\text{Y}$ beta sources.

The equivalent dose (D_e) of quartz were determined using the single aliquot regenerative-dose (SAR) protocol (Murray and Wintle, 2000) with preheat at 260 °C for 10 s and cut-heat to 220 °C for regenerative doses and test doses, respectively. The quartz OSL was measured at 125 °C for 100 s. The first 1 s of the OSL signal subtracting the equivalent average signal in the last 5 s was used for D_e determination. Five regenerative doses, including a zero-dose and a recycling dose, were used for constructing OSL growth curve. Aliquots with recycling ratio falling outside of the range of 1.0 ± 0.1 and zero-dose response (usually expressed as the ratio between the sensitivity corrected OSL signals for the zero dose and natural dose, and termed the recuperation ratio) higher than 5% were discarded for D_e determination (Murray and Wintle, 2000). Medium aliquots with about 500 grains on the disc were used for OSL dating with quartz separates. 24 to 50 aliquots were used for each sample. For the K-feldspar IRSL measurements, a SAR protocol following the procedures given by Li et al. (2008b) was used. The main feature of this protocol is the uses of a 10 s preheat at 280°C ahead of both the main IRSL measurement and the test dose measurement. Isochron IRSL ages were obtained from the isochron plots of D_e values against internal dose rate (Li et al., 2008b).

The environmental dose rates were measured using several techniques for each sample. The contribution from U and Th decay chains were determined using the Thick-source alpha counting (TSAC) (Aitken, 1985). K concentration was measured using X-ray fluorescence (XRF) technique and converted to activity values (Adamiec and Aitken, 1998). Water content was calculated from the sample weights before and after drying. The contribution from cosmic ray was calculated from the burial depth and the latitude and altitude of the samples (Prescott and Hutton, 1994).

4.2 Environment proxy analysis

48 bulk samples for multi-proxy analysis were collected in 10 cm interval from the section. The grain size and total organic carbon (TOC) analyses were carried out in the Institute of Geology and Geophysics, Chinese Academy of Sciences. The grain size was measured by using two different

techniques for different samples. Coarser particles (e.g. sand samples) were dry sieved while finer samples were determined by using a computer-operated SK Laser instrument. TOC was analyzed by the antititration method which involves oxidation of the organic carbon in the medium of sulphuric acid by excessive potassium dichromate ($K_2Cr_2O_7$) and antititration of the residual potassium dichromate by ammonium ferrous sulfate (Walkley, 1947).

5 Results

5.1 Chronology

D_e values and environmental dose rates, as well as the calculated OSL ages, for each sample are summarized in Table 1. A typical D_e distribution for one of the samples (Dgw10) is shown in a radial plot in Fig. 4. The tight distribution of the D_e values indicates that there is a single dose population, suggesting that the grains were well bleached prior to deposition (Li, 1994). Samples showed favorable behavior in OSL equivalent dose measurements, with good recycling ratio and dose recovery. The ages were obtained using the weighted mean of the D_e values. All ages fall within the Holocene, ranging from 8.5 ± 1.0 ka to 2.2 ± 0.1 ka.

All the quartz D_e values, environmental dose rates and quartz OSL ages were plotted against sample depth in Fig. 5. The D_e values are generally in stratigraphical order, i.e. the value increases with depth. However, age reversal was observed for three samples (Dgw2, Dgw3 and Dgw4) between 150-200 cm (red symbols in Fig. 5). It is noted that the U and Th contents for these three samples are significantly higher than others in the section (Fig. 5). This has been attributed to variation in environmental dose rate after deposition due to recent uptake of uranium/thorium (Li et al., 2008a). This causes overestimation of the environmental dose rates, which is inferred from the present-day dose rate (red symbols in Fig. 5). Hence, the quartz OSL ages for these samples are significantly underestimated, resulting in OSL age reversal at this section.

To overcome the problem of dose rate changing, samples Dgw3, Dgw4 and Dgw5 were studied using isochron IRSL dating using K-feldspar of different grain sizes (Li et al., 2008a; Li et al., 2008b).

Since the isochron method is reliant on only the internal dose rate, it overcomes problems related to (1) changes in past dose rate due to post-depositional migration of radionuclides, (2) changes in water content as waterlain sediments dry out, (3) spatial heterogeneity in the gamma dose rate, (4) uncertainties in the cosmic ray dose rate during the period of sample burial (Li et al. 2008a). It has been shown that this method can also overcome the anomalous fading problem commonly found in optical dating of K-feldspar (Li et al. 2008b). The isochron ages from Dgw3, Dgw4 and Dgw5 are shown in Table 1 and Fig. 5. It is demonstrated that, for the problematic samples Dgw3 and Dgw4, their isochron ages are consistent with the stratigraphy (empty squares in Fig. 5). For the sample Dgw5, the isochron age is consistent with quartz OSL age, confirming that this sample has experienced little change in environmental dose rate and the estimate of effective water content is reasonable. Based on both the quartz OSL ages and isochron ages, the chronology of the Dagouwan section has been established (Fig. 3).

5.2 Variations in climatic proxies

The variations in TOC and median particle size (Md), together with the stratigraphy and ages are shown in Fig. 3. The TOC of the sediments can be used as an indicator of vegetation cover and biomass. The studied region lies in east Asian monsoon zone, and therefore summer monsoonal rainfall has played an important role in controlling the vegetation cover (Editing Committee of Vegetation of China, 1980). The highest TOC content occurs in the lacustrine layer between 1.35 and 3.25 m, indicating that a lake formed at 8.3-5.0 ka as a result of enhanced summer monsoon during the mid-Holocene (Sun et al., 2006), whereas the basal eolian sands and uppermost fluvial sandy silt with low TOC content.

Particle size for eolian deposits is usually used as a reflection of wind energy (Pye and Zhou, 1989; Sun et al., 1999). Larger grains can be interpreted as indicating stronger winds, and the cyclic variations in grain size of the eolian sequences are thought to reflect the variable strength of winter monsoonal winds blowing from the Siberian High (Sun et al., 1999). In this study, the median particle

size variations depend on the sedimentary facies. The lacustrine unit contains the finest median grain size compared with coarser material in the underlying eolian and overlying fluvial units (Fig. 3)

6 Discussion

The history of Holocene environmental change in the study area can be reconstructed based on the environmental proxy analysis and the OSL dating results. Additionally, we also correlated the studied section with the other sites from the Mu Us Desert, in order to reconstruct the regional scale palaeoenvironment. According to the dating results and sedimentary facies from the Dagouwan section at the Sala Us river valley, Holocene environmental change can be divided into four stages.

6.1 Dry conditions and eolian activities in the early Holocene

Eolian process prevailed during the early Holocene (prior to 8.3 ka) marked by the occurrence of eolian dune sands at Dagouwan. This is also mirrored by the lowest TOC content (Fig. 3) which implies the lowest biomass in a dry episode. Sun et al. (2006) also studied the Holocene eolian deposits at two sites on the eastern boundary of the Mu Us Desert, JJ and TYG, and one site at the Hobq Desert, KB (see Fig. 1 for locations). This early Holocene eolian process can be also broadly correlated with the records from the other sites of the Mu Us Desert (Fig. 6), suggesting that widespread arid climate dominated in the Mu Us Desert during the early Holocene. Additionally, such an early Holocene dry episode is also identified in the lake records east to the Mu Us Desert (e.g., Xiao et al., 2004)

6.2 Holocene optimum (8.3-5 ka)

Lake formation took place between 8.3 and 5 ka, indicating a shift from eolian sand dunes to fine lake sediments the dry/cold climate of the early Holocene to the warm/humid climate of the middle Holocene. This is supported by the highest TOC content during this period (Fig. 3). In comparison, eolian sections in the Mu Us and Hobq desert dunes indicate pedogenesis to form soil during this time (Fig.6), which was sandwiched by the early and late Holocene eolian dune sands (Fig. 6). In the mid-Holocene sandy loam soil, pollen analysis indicate dominant herb taxa suggesting a steppe

environment (Sun et al., 2006). Therefore, the early Holocene mobile sand dunes were stabilized in a response to the enhanced humid conditions during the Holocene Optimum (Sun and Ding, 1998; Sun et al., 1999; Li et al., 2002; Li and Sun, 2006; Sun et al., 2006). Although the sedimentary facies are different among these sections, the combination of lake formation and soil dedevelopment suggest an optimal climate with warm/humid conditions. This can be explained by our conceptual model (Fig. 7). The landforms of the studied region were more diverse during the middle Holocene than at present. Lakes and playas occupied the lower lands, whereas dune sands in the higher areas (not affecting by river channels and swampy marshes) were stabilized by vegetation and then the previous sand accumulation process was replaced by soil development. Despite the different sedimentary facies, both of them indicate optimum climate during the middle Holocene due to the enhanced summer monsoon. Therefore, the co-existence of lacustrine, playa and palaeosols mostly represents diverse environments.

Additionally, our results of the mid-Holocene Optimum between 8.3 and 5 ka can be also broadly correlated with the other palaeoclimatic records from the neighboring monsoonal region of the semiarid China (Fig. 8). In the Tengger Desert, which lies in the west of the Mu Us Desert, previous studies on the palaeobeach terraces in Lake Baijian indicated that Terrace T3 and T4 formed, between 10 and 4 ka, are 13-14 m above present lake level (Fig. 8b, Pachur et al., 1995; Wunnemann et al., 1995). Lake Yiema, which is located to the west of the adjoining Tengger Desert, recorded a phase of increased moisture ca 10-4.2 ka (Fig. 8c, Chen et al., 1999). In the western margin of the Tengger Desert, multiple-studies on the deposits of the Hongshui River section indicated that warm climate prevailed from 7.500 to 5 ka (Fig. 8d, Zhang et al., 2000). In Lake Daihai, which is about 100 km northeast of the Hobq Desert, high lake level occurred from 10 to 4.3ka (Fig. 8e, An et al., 1991). Moreover, Feng et al. (2006) compiled a large amount of published data about the arid and semi-arid areas of China from both monsoonal and westerlies regions in northern China. They concluded that the Holocene optimum in these areas occurred nearly contemporaneously between 8-5 ka.

6.3 Environmental change between 5-2 ka ago

By ~5.0 ka, the warm/humid Holocene Optimum terminated, followed by lake regression and the development of fluvial systems. This fluvial process lasted to 2 ka ago (Fig. 3). In the other sites from the Mu Us and Hobq deserts, eolian activity was initiated ~5.0 ka ago (Fig. 6). The available evidence demonstrates aridification of the environment from ~5.0 ka ago, implying an enhanced winter monsoon and weakened summer monsoon during the late Holocene (An et al., 1991).

6.4 Environmental change in the most recent 2000 years

The top of the fluvial sediment gave an OSL age of 2.2 ± 0.1 ka (Fig.3) and is overlaid by modern eolian sand dunes. Although it is possible that these fluvial sediments were eroded, the thick Quaternary sediment in this area was incised by the Sala Us River after 2.2 ± 0.1 ka. Taking the present valley depth of 60-80 m, an average downcutting rate of at least 3-4 cm/year could be estimated. A similar incision rate of 4-5 cm/year was calculated by Dong et al. (1983). Based on the historical record and depth of ancient well adjacent to Sala Us River, they concluded that the Sala Us River formed and began to incise through the sediments at ~ 2 ka. Our OSL age from the top of the fluvial sediment at Dagouwan further confirms their conclusion.

Such a high downcutting rate indicates that there may have been tectonic uplift in this region over the last 2 ka; which would result in a change from fluvial sedimentation to downward erosion in this area (Sun et al., 1996). Therefore, the disappearance of the ancient lake is not only a result of increasingly dry conditions, but also of the formation of the Sala Us River and its downward incision which drained the lake.

In addition to the natural factors, such as climatic drought and river incision, human activities also have an important effect on the desertification in this area in the last 2000 years. Many relics of ancient cities were preserved in this area in the last 2000 years, but were gradually abandoned in response to active sand movement and deterioration of the local environment (Sun, 2000). Extensive agricultural activities, especially in the Tang dynasty (A.D. 800) and the late Ming (about A.D. 1500–1600) (Huang et al., 2009), destroyed a large amount of the natural vegetation cover. Meanwhile, frequent military activity and conflicts between the Han and nomads in this area over the last 2000

years resulted in the abandonment and destruction of farm land and vegetation cover, and this also accelerated the reworking of relic sand dunes (Sun, 2000). Actually, the above factors all involved in the evolution of landscape evolution since 2000 years ago. It is difficult to decouple the effect of human impacts from the natural climatic changes in the latest Holocene.

7 Conclusions

OSL dating of the lacustrine and fluvial sediments at Dagouwan, southern Mu Us Desert, indicates that the Holocene Optimum, as evidenced by the formation of lakes occurred between ~8.3 and ~5.0 ka. By ~5.0 ka, the warm/humid Holocene Optimum terminated and the climate became dry again, and this was marked by lake regression and eolian sand accumulation nearby. Fluvial sedimentation lasted from ~5 ka to ~2 ka. From about 2 ka, the Sala Us River began to incise the underlying Quaternary sediments, with a downcutting rate of ~3-4 cm/year. Generally, the Holocene environmental changes are response to the waxing and waning of the east Asian summer monsoon, but impacts of human activities also play an important role in causing environmental change during the last 2 ka.

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Figure captions:

Figure 1: Map showing the Mu Us desert, the Sala Us River, the study area (shown in square) and sections KB, JJ and TYG (Sun et al 2006).

Figure 2: Map showing the Sala Us River valley and the location of Dagouwan section.

Figure 3: Stratigraphy, sampling depths, TOC, median grain size (Md), and OSL ages of the Dagouwan Holocene section.

Figure 4: The radial plot showing the D_e distribution for sample Dgw10. The shaded area indicates $\pm 2\sigma$ of the central value. The values lying within $\pm 2\sigma$ of the central value are shown as filled symbols, and those outside $\pm 2\sigma$ of the central value are shown as empty symbols.

Figure 5: The quartz equivalent dose (D_e) values, Environmental dose rate and OSL ages plotted against sampling depth. The blue diamonds represent the samples with no problem in environmental dose rate. The red diamonds represent those samples with problematic environmental dose rate. The empty squares are the isochron dating results.

Figure 6: Correlation of the stratigraphies at Dagouwan section and KB, JJ and TYG sections (Sun et al., 2006).

Figure 7: Comparison of the Holocene environmental evolution at Dagouwan (a), with the lake level changes of Lake Baijian (b, Pachur, H.J., 1995; Wünnemann, B. et al., 1998), the moisture index variations of Lake Yiema (c, Chen, F.H., 1999), the temperature changes recovered from the Hongshui River section (d, Zhang, H.C., 2000), the lake level fluctuations of Lake Daihai (e, An et al., 1991).

Fig. 1

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