Full length article

Optical dating of eolian deposits since the last interglacial along the northern margin of the Chinese Loess Plateau

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A R T I C L E   I N F O

Keywords:
OSL
Quartz
K-feldspar
SAR
MET-pIRIR

A B S T R A C T

Understanding the chronology of eolian sand-loess-paleosol sequences along the northern margin of the Chinese Loess Plateau (CLP) is crucial for comprehending climate change and the advance and retreat of the adjacent Mu Us desert. In this study, a sand-loess-soil sequence from the northern margin of the CLP was studied by applying the single aliquot regenerative (SAR) protocol to quartz grains, and the multi-elevated-temperature post-IR IRSL (MET-pIRIR) protocol to K-feldspar grains. For equivalent dose (De) determination, 63–90μm quartz and K-feldspar grains were used. Our results indicate that the MET-pIRIR ages of K-feldspar grains in this sequence range from 94.4 ± 7.0 ka to 148.3 ± 13.3 ka for the last interglacial paleosol (S1); for the upper part of the section, quartz-based SAR-OSL dating was used, yielding ages spanning from 5.8 ± 0.4 ka to 35.9 ± 4.1 ka. After cross-checking these results with previously-reported isochron OSL and TL ages, the reliability of the MET-pIRIR protocol to K-feldspar grains was confirmed. Based on a new OSL chronology of the Shimao profile, the studied eolian deposits can be broadly correlated with the last glacial-interglacial cycle, but their dating also points to sedimentary hiatuses occurring at 94.4 ka, 35.9 ka and 5.8 ka, due most probably to strong wind erosion caused by intensified cold-dry winter monsoonal circulations during the last glacial maxima.

1. Introduction

Luminescence dating has been widely used to date loess and eolian sands in the arid and semi-arid China (Watanuki et al., 2003, 2005; Wang et al., 2006a,b; Lai, 2006, 2010; Lai and Wintle, 2006; Li et al., 2007; Lu et al., 2007; Roberts, 2008; Kang et al., 2011, 2012, 2013; Stevens et al., 2013; Chen et al., 2015; Ankjærgaard et al., 2016). Quartz and feldspar minerals are suitable for optically stimulated luminescence (OSL) dating because their latent luminescence signals can be erased (zeroed) when the minerals have been sufficiently exposed to sunlight during their transportation, allowing the subsequent calculation of cumulative dose to be used to date the time at which the minerals concerned have been buried. Considering the different luminescence behaviors of quartz and K-feldspar, it is necessary to use both quartz and K-feldspar grains in OSL dating to cross check dating results.

The quartz-based SAR protocol remains the mostly widely-used method for quantifying paleodoses (Murray and Wintle, 2000, 2003; Wintle and Murray, 2006). As a general rule, this protocol can be applied to many types of sediments (Murray and Olley, 2002). Loess is an ideal sediment for OSL dating, and numerous quartz OSL ages have been reported in the last decade which have been determined using the SAR protocol (e.g., Roberts and Wintle, 2001; Stokes et al., 2003; Watanuki et al., 2003; Küster et al., 2006; Buylaert et al., 2007; Lai, 2010; Yi et al., 2015). The quartz OSL SAR growth curve increases linearly in the higher ~200–1000 Gy dose range, allowing a De determination of >400 Gy (Watanuki et al., 2003, 2005; Buylaert et al., 2008; Lai, 2010; Lowick et al., 2010; Lowick and Preusser, 2011; Lai and Fan, 2013). However, the quartz OSL signal is not as stable as previously thought, and age underestimations are possible (Buylaert et al., 2008; Qin and Zhou, 2009; Lai, 2010; Chapot et al., 2012; Lai and Fan, 2013). It is therefore preferable that any potential luminescence dose saturation of quartz grains be analyzed alongside OSL dating.

Compared with quartz, K-feldspar is a more suitable for dating older samples because of its higher saturation doses and thermal stability. In addition the feldspar OSL has more advantages such as brighter intensity, higher reproducibility, and greater precision (e.g., Li et al., 2007; Li and Li, 2011, 2012b; Chen et al., 2015).

Over the past two decades, attempts have been made to correct, or...
to avoid, the effect caused by the anomalous fading of K-feldspar OSL signals (e.g., Sanderson and Clark, 1994; Lamothe and Auclair, 1999; Huntley and Lamothe, 2001; Zhao and Li, 2002; Auclair et al., 2003; Lamothe et al., 2003; Tsukamoto et al., 2006; Kars et al., 2008; Li et al., 2008; Li and Li, 2011) and the consequent limitations placed upon infrared-stimulated luminescence (IRSL) dating (Wintle, 1973). Recent studies have shown that the two-step post-IR IRSL (pIRIR) protocol (e.g., Thomsen et al., 2008; Buylaert et al., 2009; Thiel et al., 2011) and the multiple-elevated-temperature post-IR IRSL (MET-pIRIR) protocol (e.g., Li and Li, 2011, 2012a,b) can be successfully used to date different types of sediment and yield effective $D_e$ values (e.g., Buylaert et al., 2012; Li et al., 2014).

The Shimao section is located in the transition zone between the Mu Us Desert and the CLP and, as such, can reflect periods of advance and retreat of the Mu Us Desert in response to the waxing and waning of the East Asian Monsoon (EAM; Sun and Ding, 1998; Sun et al., 1999). Several OSL ages obtained from the Shimao section have been previously reported, using either TL dating (Sun et al., 1998, 1999), isochron IRSL dating (Li et al., 2008, 2011) or MET-pIRIR dating (Fu and Li, 2013; Li et al., 2013, 2014, 2015). Especially the quartz grains or feldspar grains of this section are ideal for studying the luminescence method due to its similar geologic source, which indicate that they are likely to have similar characteristics and transportation and deposition history (Li and Li, 2008). However, various geological ages do not usually match each other using different luminescence methods. Therefore, cross-checking with different luminescence dating methods is necessary to rebuild the OSL chronology of Shimao section. In addition, more OSL ages of eolian deposits from the S1 to S0 units should be presented in order to further discuss climatic change during this period.

In this study, we used both the quartz-based SAR and the K-feldspar-based MET-pIRIR protocols. This paper has three main objectives: 1) to examine the OSL saturation characteristics of coarse quartz grains with different ages; 2) to cross-check quartz and K-feldspar ages using the SAR and the MET-pIRIR protocols, respectively; and 3) to establish a relatively solid chronology of sand-loess-soil sequences found along the northern margin of the CLP.

2. Geological setting and sampling

The Shimao section (37°56′24″N, 109°59′01″E) is located on the boundary between the Mu Us Desert and the CLP (Fig. 1). This area is particularly sensitive to the advance and retreat of the Mu Us Desert (Sun et al., 1999). Within the section, eolian sands are intercalated within the loess and paleosol horizons. The stratigraphic units that constitute the eolian sequence fall into three categories: eolian sand beds; loess beds; and paleosols (Sun et al., 1999). It is worth noting that most loess (L) and paleosols (S) strata within the Shimao section contain interbedded loess or sand layers; these are subdivided by hyphenating and adding a number to the layer, e.g., L1-1 and S1-1, following the scheme of Rutter et al. (1991) (Fig. 2).

Our study focused mainly on the upper part of the Shimao section (Fig. 2), which is ~15 m thick. The uppermost unit of the section is a ~1 m thick sandy loam (S0), with a black-brown (7.5 YR 3/2, dry) A

![Fig. 1. Map showing the Chinese Loess Plateau (CLP) and the location of the Shimao profile.](image)

![Fig. 2. Stratigraphy, sample positions and MS curves for the Shimao section. Ten OSL samples (SM-OSL-01 – SM-OSL-10) were collected for dating.](image)
horizon. Below S0 there is a ∼9 m thick eolian sequence (L1) consisting of three eolian sand beds (L1-1, L1-3, L1-5), and two interbedded loess layers (L1-2 and L1-4). The eolian sands are loose and are dull yellow-orange (10 YR 7/4, dry) to orange (7.5 YR 7/6) in color. The loess layers are dull yellow orange and moderately well-consolidated. Below L1 there is an eolian sequence (S1) consisting of three dull orange paleosols (S1-1, S1-3 and S1-5) and two interbedded silt loess beds (S1-2 and S1-4). The paleosols are dull orange (7.5 YR 7/4) to bright brown (7.5 YR 5/6) in color, and contain secondary carbonate mycelia or small carbonate nodules. Another eolian sand layer of weakly consolidated sandy grains (L2) underlies S1-5, and is orange in color (7.5 YR 7/6).

In order to obtain the chronology of this section, a total of ten OSL samples were collected (Fig. 2). They were collected by hammering steel tubes into freshly-cleaned sections. The tubes were immediately covered with black plastic bags to ensure the samples retained any natural water content.

In order to compare any paleo-environmental changes with the deep-sea oxygen isotope record, 91 bulk samples were collected (at 10 cm intervals within paleosols, and 20 cm intervals within all other layers) for magnetic susceptibility measurement.

3. Methods

3.1. Sample preparation

All OSL samples were prepared under subdued red light. The material at the end of the tubes (∼3 cm in length) was removed first and used for water content and dose rate measurements. The inner materials of the tubes were then water-washed using an ultrasonic cleaning machine. They were subsequently treated with 10% HCl and 10% H2O2 to remove any carbonates and organic material, respectively. 63–90 μm quartz and K-feldspar grains were extracted by dry sieving. Subsequently heavy liquid separation was employed using an aqueous solution of sodium polytungstate to extract the quartz and the potassium-rich feldspar (K-feldspar). We isolated the quartz fractions with densities lighter than 2.58 g/cm3 for study.

3.1.2. Instruments

The K-feldspar grains were etched using 10% HF for 40 min in order to remove any remaining K-feldspars, and their alpha irradiated outer layer. As a rule, the IRSL signal and the 110 °C thermoluminescence (TL) peak was detected through a combination of Schott BG-39 and BG-3 instruments. The luminescence analysis of the sand-size s and in their sur-

3.1.3. OSL measurement

The purified grains were mounted on aluminum steel discs using silicone oil spray. The luminescence analysis of the sand-size (63–90 μm) quartz grains was performed using the SAR protocol (Murray and Wintle, 2000, 2003). First, a preheat plateau test was conducted. A range of preheat temperatures from 180 to 280 °C was tested for sample SM-OSL-01. Fig. 3a shows that the preheat plateau fell between 220 and 260 °C. A preheated temperature of 260 °C for 10 s was therefore selected for D0 determination, with a fixed cut-point of 220 °C (Murray and Wintle, 2003). A dose recovery test was then used to test the reliability of the SAR protocol in estimating the dose. Six aliquots of sand-size quartz grains for samples SM-OSL-01 were given a 20 Gy beta dose following optical bleaching by blue LED stimulation. The SAR sequence was then applied to estimate the De value. Fig. 3b shows the dose recovery test result for Sample SM-OSL-01. The mean ratio of observed dose to given dose was 0.99 ± 0.01. This result confirmed the suitability of the preheat temperature, the test dose and the temperature of the fixed cut-point.

Recycling ratio and recuperation tests were also applied to quartz aliquots, as in any routine SAR protocol (Murray and Wintle, 2000, 2003). Murray and Wintle (2000) suggested that an acceptable recycling ratio should fall within a 0.90–1.10 range. A valid recuperated OSL signal should be equal to 0–5% of the natural signal (Atik et al., 1988; Murray and Wintle, 2000).

The quartz OSL signals from all the samples in our study exhibit a rapid decay during optical stimulation (Fig. 4). This would indicate the predominance of a fast component. A representative SAR growth curve was fitted to a single saturating exponential function, and the equivalent dose obtained by comparing the result with the natural OSL intensity (Fig. 4). For each sample, at least 24 aliquots were used to calculate D0.

Although the SAR protocol has been proven to be useful for analyzing quartz grains of young samples, the accurate OSL dating of quartz has often been hampered by lower saturation levels, as compared to K-feldspar. Therefore it is necessary to study the dose saturation behavior of quartz OSL signals. Atik et al. (1998) built a single saturation exponential function in the form of I = I0 (1 − exp (−D/D0)), where I is the OSL intensity due to dose D (Gy), Imax is the saturation luminescence intensity, and D0 (Gy) is the characteristic dose level of the dose response curve (DRC). To acquire a reliable estimation of the natural dose for quartz grains, the D0 used must be < 2D0 (Wintle and Murray, 2006).

Alternatively, the MET-pIRR protocol has been used for the optical dating of K-feldspar (Li and Li, 2011). It measures the IRSL signal by progressively increasing the stimulation temperature from 50 to 250 °C in 50 °C steps. This K-feldspar dating method has been proven to yield reliable ages and avoid anomalous fading corrections (Li and Li, 2011; Chen et al., 2015).

The environmental (or external) dose rate originates from the radioactive elements existing in the sample’s grains and in their surrounding sediment, with a contribution from cosmic rays. The uranium (U), thorium (Th), and potassium (K) contents were measured using Inductively Coupled Plasma Mass Spectrometry (ICP-MS) at the Analytical Laboratory of the Beijing Research Institute of Uranium Geology (Bailey et al., 2003). U, Th and K concentrations were converted into β and γ dose rates (Atik et al., 1985). The cosmic ray contribution was estimated from the burial depths of samples, and the latitude and longitude of the section (Prescott and Hutton, 1994). The water content was calculated by weighing each sample before, and after, drying. The internal dose rate for K-feldspar used in age calculations was estimated by assuming K = 12.5 ± 0.5% and Rb = 400 ± 100 ppm (Huntley and Baril, 1997; Huntley and Hancock, 2001; Zhao and Li, 2005; Li et al., 2008).

3.2. Magnetic susceptibility measurement

Samples for magnetic susceptibility analysis were air-dried. A Bartington MS2 instrument was used to measure the mass magnetic susceptibility of the bulk samples in the laboratory of the Institute of Geology, Chinese Academy of Sciences.
4. Results

4.1. Luminescence dose saturation behavior for quartz grains in the Shimao section

We studied the dose saturation behavior of the quartz grains in Sample SM-OSL-05 from the Shimao section. A routine SAR protocol was applied to each aliquot. The regenerative doses were set at 0, 41.5, 124.5 and 207.5 Gy, and the test dose was 41.5 Gy. A repeated dose of 41.5 Gy was used to check the reproducibility of corrections made to compensate for sensitivity. 18 aliquots were tested and the mean $L_x/T_x$ values for all the aliquots were subsequently obtained. A SAR dose response curve was then built by combining these average values and the regenerative doses. This curve was fitted to a single saturation exponential function and the mean $D_0$ was obtained. The mean $D_0$ value for Sample SM-OSL-05 was $\sim 78.0$ Gy (Fig. 5).
4.2. OSL ages of quartz grains using the SAR protocol

The OSL dose distributions of De measurements for samples SM-OSL-01, SM-OSL-02, SM-OSL-03 and SM-OSL-04 are shown in Fig. 6 as histograms. The De distributions follow a normal pattern. The mean De values for samples SM-OSL-01 to SM-OSL-04 inclusive are 18.1 ± 0.9 Gy, 38.2 ± 2.9 Gy, 37.6 ± 3.8 Gy and 106.3 ± 11.3 Gy, respectively.

In order to study the dose saturation behavior of the quartz grains in Sample SM-OSL-05, the mean De value of this sample is also listed in Table 1, which is 218.4 ± 29.9 Gy.

The OSL ages for the above five quartz OSL samples were calculated using equivalent dose by dose rates (Table 1). In the Shimao section, the ages of the five quartz OSL samples appear to increase with depth.

4.3. OSL ages of K-feldspar grains using the MET-pIRIR protocol

Due to the luminescence dose saturation behavior exhibited by the quartz grains in Sample SM-OSL-05, K-feldspar, which can sustain much higher saturation doses, was used to extend the luminescence dating limits for samples SM-OSL-05 to SM-OSL-10. The MET-pIRIR protocol adopted for De determination was used followed Li and Li (2011). Different IRSL signals were measured by progressively increasing the stimulation temperature from 50 to 250 °C in 50 °C steps, using one

Table 1

<table>
<thead>
<tr>
<th>Sample no.</th>
<th>Object</th>
<th>Depth (m)</th>
<th>Aliquots</th>
<th>De (Gy)</th>
<th>U (ppm)</th>
<th>Th (ppm)</th>
<th>K (%)</th>
<th>Water content (%)</th>
<th>Cosmic dose (Gy/ka)</th>
<th>Dose rate (Gy/ka)</th>
<th>Age (ka)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SM-OSL-01</td>
<td>Quartz</td>
<td>0.2</td>
<td>26</td>
<td>18.1 ± 0.9</td>
<td>1.15</td>
<td>5.67</td>
<td>2.31</td>
<td>3</td>
<td>0.22</td>
<td>3.14 ± 0.14</td>
<td>5.8 ± 0.4</td>
</tr>
<tr>
<td>SM-OSL-02</td>
<td>Quartz</td>
<td>1.0</td>
<td>26</td>
<td>38.2 ± 2.9</td>
<td>1.11</td>
<td>5.46</td>
<td>2.16</td>
<td>5</td>
<td>0.20</td>
<td>2.88 ± 0.12</td>
<td>13.3 ± 1.2</td>
</tr>
<tr>
<td>SM-OSL-03</td>
<td>Quartz</td>
<td>2.7</td>
<td>35</td>
<td>37.6 ± 3.8</td>
<td>0.59</td>
<td>2.17</td>
<td>2.29</td>
<td>1</td>
<td>0.16</td>
<td>2.72 ± 0.12</td>
<td>13.8 ± 1.5</td>
</tr>
<tr>
<td>SM-OSL-04</td>
<td>Quartz</td>
<td>3.4</td>
<td>24</td>
<td>106.3 ± 11.3</td>
<td>2.34</td>
<td>10.00</td>
<td>1.86</td>
<td>8</td>
<td>0.08</td>
<td>2.97 ± 0.12</td>
<td>35.9 ± 4.1</td>
</tr>
<tr>
<td>SM-OSL-05</td>
<td>Quartz</td>
<td>10.1</td>
<td>12</td>
<td>218.4 ± 29.9</td>
<td>2.27</td>
<td>10.60</td>
<td>1.93</td>
<td>11</td>
<td>0.07</td>
<td>2.96 ± 0.12</td>
<td>73.9 ± 10.5</td>
</tr>
<tr>
<td>SM-OSL-05</td>
<td>K-feldspar</td>
<td>10.1</td>
<td>8</td>
<td>311.9 ± 20.1</td>
<td>2.27</td>
<td>10.60</td>
<td>1.93</td>
<td>11</td>
<td>0.07</td>
<td>3.31 ± 0.12</td>
<td>94.4 ± 7.0</td>
</tr>
<tr>
<td>SM-OSL-05</td>
<td>K-feldspar</td>
<td>10.7</td>
<td>8</td>
<td>331.0 ± 18.1</td>
<td>2.35</td>
<td>10.60</td>
<td>1.93</td>
<td>14</td>
<td>0.06</td>
<td>3.23 ± 0.11</td>
<td>102.5 ± 6.6</td>
</tr>
<tr>
<td>SM-OSL-07</td>
<td>K-feldspar</td>
<td>13.2</td>
<td>7</td>
<td>377.7 ± 24.0</td>
<td>2.47</td>
<td>9.79</td>
<td>1.97</td>
<td>10</td>
<td>0.05</td>
<td>3.34 ± 0.12</td>
<td>113.2 ± 8.3</td>
</tr>
<tr>
<td>SM-OSL-08</td>
<td>K-feldspar</td>
<td>13.7</td>
<td>10</td>
<td>408.6 ± 33.9</td>
<td>2.52</td>
<td>10.30</td>
<td>1.90</td>
<td>6</td>
<td>0.05</td>
<td>3.45 ± 0.13</td>
<td>119.1 ± 10.9</td>
</tr>
<tr>
<td>SM-OSL-09</td>
<td>K-feldspar</td>
<td>14.6</td>
<td>8</td>
<td>408.7 ± 31.5</td>
<td>1.75</td>
<td>7.89</td>
<td>1.91</td>
<td>3</td>
<td>0.05</td>
<td>3.20 ± 0.13</td>
<td>125.4 ± 11.2</td>
</tr>
<tr>
<td>SM-OSL-10</td>
<td>K-feldspar</td>
<td>15.4</td>
<td>11</td>
<td>459.9 ± 36.9</td>
<td>1.42</td>
<td>6.17</td>
<td>1.99</td>
<td>2</td>
<td>0.04</td>
<td>3.10 ± 0.13</td>
<td>148.3 ± 13.3</td>
</tr>
</tbody>
</table>
aliquot. Fig. 7 shows various sensitivity-corrected DRCs observed for different stimulation temperatures for Sample SM-OSL-06. All of the DRCs were fitted to single exponential saturation functions. These fitting results suggested that the 50 °C, 100 °C, 150 °C and 200 °C steps all exhibited similar saturation doses ($D_0 = 468.5 \pm 20.8$ Gy, $416.0 \pm 22.1$ Gy, $397.7 \pm 26.8$ Gy and $350.0 \pm 21.7$ Gy, respectively). However, the 250 °C signal exhibited a lower saturation dose of $291.8 \pm 34.6$ Gy. The earlier saturation doses exhibited by high temperatures have been noted in previous studies (Li and Li, 2011; Thomsen et al., 2011; Li et al., 2014), meaning that it is reasonable to assume that more stable signals are more quickly saturated than the less stable signals. Our results would suggest that the upper dose limit for the 250 °C signal for Sample SM-OSL-05 is $\sim 584$ Gy (corresponding to a date of 176 ka), when using sensitivity-corrected signals ($L_x/T_x$).

Based on the original MET-pIRIR protocol proposed by Li et al. (2011), an age-temperature (A-T) plot was built to allow a comparison of the MET-pIRIR ages with the corresponding IR stimulation temperatures. Li and Li (2011) considered that the 250 °C MET-pIRIR signal yields the most reliable result, and that there is negligible anomalous fading for the signals measured at this temperature. In this paper, we also found that ages tended to increase when the stimulation temperature increased from 50 to 200 °C, with age plateau at 200 °C and 250 °C (Fig. 8). We therefore adopted the ages obtained using the 250 °C signal as indicative of the true ages of the K-feldspar samples (Table 1).

For samples SM-OSL-05 and SM-OSL-06, collected from layer S1-1, the MET-pIRIR (250 °C) signal gave ages of $94.4 \pm 7.0$ ka and $102.5 \pm 6.6$ ka, respectively. The MET-pIRIR (250 °C) ages of samples SM-OSL-07 and SM-OSL-08, collected from the boundaries S1-2/S1-3 and S1-3/S1-4, were $113.2 \pm 8.3$ ka and $119.1 \pm 10.9$ ka, respectively. We calculated the age of Sample SM-OSL-09, collected from the bottom of layer S1, to be $125.4 \pm 11.2$ ka. Sample SM-OSL-10, collected from the top of layer L2, yielded an age of $148.3 \pm 13.3$ ka.

4.4. Magnetic susceptibility variations in the Shimao section

The vertical variations of magnetic susceptibility have been explained by differences in parent materials and the post-depositional pedogenesis (Sun et al., 1999).

5. Discussion

5.1. Growth curve saturation levels for quartz grains

The saturation doses for the quartz grains in Sample SM-OSL-05 are shown in Fig. 5. The $D_0$ value is $\sim 156$ Gy, greater than the obtained $D_0$ values for the samples SM-OSL-01, SM-OSL-02, SM-OSL-03 and SM-OSL-04. It can be safely assumed, therefore, that values for the latter four samples fall well below quartz OSL saturation levels, and that, accordingly, their quartz OSL ages are reliable. However, the $D_0$ value for Sample SM-OSL-05 is $218.4 \pm 29.9$ Gy (equivalent to an age of $\sim 73.9 \pm 10.5$ ka). Problematically, this value is $> 2D_0$ (i.e., $\sim 156$ Gy). It would appear, therefore, that the quartz OSL age for Sample SM-OSL-05 determined using the SAR protocol represents an underestimate, especially based on a comparison with the MET-pIRIR dating results (Table 1).

5.2. Cross-checked quartz and K-feldspar ages in the Shimao section

In order to construct a reliable chronology, therefore, we deemed it indispensable to cross-check the ages we obtained with the ages yielded by using different dating techniques, including the SAR and MET-pIRIR protocols, TL dating and isochron dating which have been obtained in previous works (Sun et al., 1998, 1999; Sun and Ding, 1998; Li et al., 2011, 2014, 2015; Li and Li, 2008; Fu and Li, 2013). The resulting OSL data sets were collated, and are shown in Fig. 9. It is clear from these datasets that the four samples SM-OSL-01, SM-OSL-02, SM-OSL-03 and SM-OSL-04 all have strong, dominant fast-component OSL signals, as well as $D_0$ values below the $2D_0$ limit. The SAR protocol can therefore be taken as appropriate for dating the upper part of the Shimao section.

In addition, the MET-pIRIR protocol has already been successfully applied to the coarse-grained K-feldspar grains found in six samples from the Shimao section, proving that the non-fading component of the IR signals of K-feldspar can easily be identified (Li and Li, 2011; Li et al., 2013). For all the samples subjected to the MET-pIRIR protocol, $D_0$ values and ages obtained at 200 °C increased with depth. It is worth noting that the MET-pIRIR ages obtained are mostly consistent with the TL ages (based on the stratigraphic correlation shown in Fig. 9; Sun et al., 1998). Some researchers have proposed that the IR signals of K-feldspars stimulated at an elevated temperature ($> 200$ °C) fade much more than those stimulated at 50 °C (Thomsen et al., 2008; Buylaert et al., 2009; Thiel et al., 2011; Li et al., 2013). Li and Li (2011) have studied the fading signals of Sm08 collected from the Shimao section and their conclusion is that a negligible anomalous fading was observed for the MET-pIRIR signals at 200 and 250 °C. Our result also shows similar $D_0$ values were obtained for the MET-pIRIR signal at 200 and 250 °C, which also indicate the MET-pIRIR signals (at 250 °C) are slightly affected by fading. These results further confirm that the MET-pIRIR signal observed at 250 °C can give reliable results for samples dating from the last full glacial cycle.

We cross-checked the SAR and MET-pIRIR ages we obtained from the Shimao section with six pre-recorded TL ages (Sun et al., 1998) and another six isochron ages (Li et al., 2011) from the same section (Fig. 9). The six TL ages were collected from units S1-1 to S1-5 by Sun et al. (1998) and yielded ages between $134 \pm 11$ ka and $83 \pm 7$ ka. In this study, the MET-pIRIR ages for S1-1 to S1-5 ranged from $148.3 \pm 13.3$ ka to $94.4 \pm 7.0$ ka, if the error bars are considered, mostly consistent with the previous TL ages.

In general, the OSL SAR ages are broadly consistent with the isochron results for three samples (i.e., SM1, SM04-04 and SMS) reported by Li et al. (2011). However, there are some differences between them,
evinced by samples SM4, SM-OSL-05 and TL-67. All these latter samples were collected near the S1/L1 boundary in the Shimao section. The MET-pIRIR age of Sample SM-OSL-05 and the TL age of Sample TL-67 are 94.4 ± 7.0 ka and 83 ± 7 ka, respectively. The isochron age of SM4 is ∼40 ± 5.6 ka. The isochron age of SM4 is obviously much younger than the MET-pIRIR and TL ages, and is also younger than the age of the last interglacial (S1)/glacial (L1) boundary. The IRSL age of SM4 is ∼37 ± 2 ka, very similar to the isochron age. We can therefore safely infer that the isochron and IRSL ages are both underestimates. Isochron dating limits, and any resultant underestimates of age, have already been related to the anomalous fading that may have occurred during the application of both internal and external doses to such samples (Li et al., 2011). The MET-pIRIR protocol is therefore more suitable than isochron dating when attempting to establish the ages of the K-feldspar grains found in the Shimao section.

Fig. 8. MET-pIRIR ages for samples SM-OSL-07 and SM-OSL-09 obtained using the MET-pIRIR protocol. Ages tended to increase as the stimulation temperature increased from 50 to 200 °C, with age plateaus at 200 °C and 250 °C.

Fig. 9. Cross-correction between the SAR ages, MET-pIRIR ages, isochron IRSL ages and TL ages for the Shimao section. The isochron IRSL ages (purple stars) and sample positions are taken from Fig. 6 of Li et al. (2011). The TL ages (green rectangles) and sample positions are taken from Sun et al. (1998).
Our new OSL ages from the Shimao section fall between 148.3 ± 13.3 ka and 5.8 ± 0.4 ka, confirming that the upper part of the section accumulated during the last interglacial-glacial cycle. With the help of these new OSL ages, the measured magnetic susceptibility curve can be broadly correlated with the marine SPECMAP record (Imbrie et al., 1984) (Fig. 10).

The top loam corresponds to Marine Isotope Stage 1 (MIS1). Its age of 5.8 ± 0.4 ka suggests that there has largely been a sedimentary hiatus after this time. This can be explained by the change from a period of warm-humid soil development to a cold-dry dune mobilization in the desert-loess transition zone of this region after the Mid-Holocene Optimum (Sun et al., 2006).

The last glacial period was marked by desert expansion and an accumulation of loess in the Shimao section under cold-dry climatic conditions. It is worth noting that there is an age gap between the L1-1 and L1-2 units (Fig. 10), suggesting that there was sedimentary hiatus during MIS 2. This could be explained by the dominant cold-dry winter monsoonal circulation, as well as high-energy wind erosion in the desert-loess transition zone during the last glacial maximum (LGM).

The last interglacial was characterized by three phases of soil development broadly corresponding to MIS 5a, 5c and 5e, and two loess accumulation stages corresponding to MIS 5b and 5d (Fig. 10). Samples dating near the top of S1-1 yielded an age of 94.4 ± 7.0 ka, being older than the 90–74 ka of MIS 5a, suggesting the existence of another sedimentary hiatus at the site of the Shimao section. Considering the large error bar of the age of S1-1, it should be correlated with MIS 5a. The dominant East Asian Winter Monsoon (EAWM), driven by an intensified high-latitude Siberian High during the cold-dry stage of MIS 4, could account for the wind erosion on the previous accumulated paleosol of S1-1 during MIS 5a, leading to the sedimentary hiatus on the top of this soil in the desert-loess transition zones of northern China.

6. Conclusions

OSL SAR and MET-pIRIR dating techniques were used to analyze samples from the Shimao section on the northern margin of the CLP, resulting in the following conclusions:

(1) A study of the saturation behavior of quartz grains from the Shimao section determined that the $D_0$ values of the uppermost four samples (i.e., samples SM-OSL-01 to 04, inclusive) obtained using the quartz OSL SAR protocol fell below the $2D_0$ limit. Conversely, the SAR quartz protocol underestimated the age of Sample SM-OSL-05, due to the dose saturation limits of quartz grains, and was therefore deemed unsuited to dating older samples.

(2) When the MET-pIRIR protocol was applied to K-feldspar grains, it gave reliable ages for the older samples collected from the last interglacial paleosol (S1), as confirmed by cross-checking with previously-recorded isochron OSL and TL ages.

(3) Using these newly-acquired OSL ages, the eolian deposits of the upper part of the Shimao section can be broadly correlated with the last glacial-interglacial cycle, but sedimentary hiatuses also appeared especially during the high-energy wind erosion states typical of MIS 2 and 4, when the studied region was mostly a dust source affected by an intensified cold-dry east Asia winter monsoon circulation.

Acknowledgements

This work was financially supported by grants from the Natural Science Foundation of China (Grant No. 41302148), the Chinese Geological Survey Project (Grant No. 121201104000150009), the Basic Science Foundation of the Chinese Academy of Geological Sciences (Grant No. YYWF201518) and the Basic Science Foundation of the Institute of Geomechanics (Grant No. DZLXJK201714).
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