On the Bleaching Degree of Multi-Grain Coarse Quartz OSL Signal of Near-Surface Aeolian Sediments Around the Tengger Desert: Empirical Investigation and Numerical Validation

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In this study, the degree of bleaching of multi-grain coarse quartz optically stimulated luminescence (OSL) signal of near-surface aeolian samples collected around the Tengger Desert is assessed. The single-aliquot regenerative dose (SAR) protocol and the standardized growth curve (SGC) method are applied to measure the equivalent dose ($D_e$) of these samples. The bleaching degree of the samples is assessed by investigating 1) the relationship between $\ln/\ln$ and SAR $D_e$ and 2) the SGC $D_e$ distribution. Various degrees of heterogeneously-bleached multi-grain dose distributions synthetized with a numerical simulation method is further used to validate the bleaching performance of the samples. It demonstrates that the investigated samples are characterized by tight $D_e$ distributions and the maximum $D_e$ estimate is smaller than 1.1 Gy. The numerical simulation method which uses as input a large proportion of fully-bleached grains and a small baseline dose is able to reproduce multi-grain $D_e$ distributions similar to the measured ones. We conclude that OSL signals of multi-grain coarse quartz extracted from most of the investigated aeolian samples are fully bleached before deposition.

Keywords: quartz OSL dating, multi-grain aliquots, aeolian sediments, bleaching degree, tengger desert

INTRODUCTION

Optically simulated luminescence (OSL) dating techniques are widely used for the determination of the burial ages of Quaternary sediments (e.g., Li et al., 2002, 2014; Zhao et al., 2007; Yi et al., 2015; Peng et al., 2022). To obtain accurate OSL ages, optically sensitive charges that were previously accumulated in the mineral (quartz and feldspar) grain should be completely zeroed (or bleached) by sunlight prior to the last deposition of sediments (Godfrey-Smith et al., 1988; Peng et al., 2020). However, heterogeneous bleaching of quartz OSL signals has been frequently reported in the literature, especially for younger sediments with smaller equivalent dose ($D_e$) values (e.g., Lian and Huntley, 1999; Li, 2001; Zhang et al., 2003; Olley et al., 2004; Arnold et al., 2009; Pietsch, 2009; Hu et al., 2010; Costas et al., 2012; Ou et al., 2015; Mahadev et al., 2019).

Aeolian sediments are the most readily available materials for OSL dating in semi-arid/arid regions (Peng et al., 2022), and are thought to be the most unlikely influenced by heterogeneous bleaching (Wintle, 1993) due to their longer time of exposure to sunlight before deposition compared to water-lain sediments. Although many authors reported that their aeolian samples under analyzed were fully bleached before deposition (e.g., Bailey et al., 2001; Ballarini et al., 2003; Stokes et al., 2004;
Singarayer et al., 2005; Zhao et al., 2012; Gong et al., 2013; Fu et al., 2015; Long et al., 2019; Yang et al., 2020), there is a growing lines of evidence indicating that it is not a sufficient guarantee that aeolian sediments under all deposition environments were fully bleached (e.g., Lian and Huntley, 1999; Spooner et al., 2001; Goble et al., 2004; Olley et al., 2004; Tissoux et al., 2010; Costas et al., 2012; Fan et al., 2013, 2022; Buckland et al., 2019). Accordingly, it is important to assess the bleaching degree of aeolian sediments in a region-specific scale to obtain accurate OSL ages for young samples to establish reliable geochronological framework on a century to decadal time scale.

Tengger Desert is a major proximal desert upwind to the Chinese Loess Plateau and aeolian dust released therein has significantly influenced region- and hemisphere-scale environments (Peng et al., 2022). Fan et al. (2013) assessed the bleaching degree of fine-grained quartz (11–63 μm) OSL signals near the Lanzhou city 200 km south to the Tengger Desert and indicated that most (but not all) the investigated samples were fully bleached. Fan et al. (2022) investigated the bleaching degree of coarse-grained quartz (90–125 μm) OSL signal of dune sands from the hinterland of the Tengger Desert and suggested that approximately a half of the studied samples were heterogeneously bleached. However, the bleaching characteristics of coarse-grained quartz OSL signals of aeolian sediments along the margin of the Tengger Desert have not been formally assessed yet, although a growing number of chronostratigraphic records from the desert margin were dated using coarse-grained quartz OSL (e.g., Qiang et al., 2010; Yin et al., 2013; Peng et al., 2016, 2022). In this study, near-surface coarse aeolian samples collected around the margin of the Tengger Desert were investigated to assess their multi-grain quartz OSL signal bleaching degrees using both empirical and numerical simulation methods.

### SAMPLES AND METHODS

Twelve aeolian samples collected from nine different sites around the margin of the Tengger Desert were investigated (Figure 1A). The maximum distance between these sites and the mobile sand sea of the desert are smaller than 60 km. Samples were collected at the near-surface of the outcrops (with an average depth of ~0.86 m) and were expected to have $D_e$ values approaching zero. Sample TDN6-4 is sandy loess and the remaining samples are aeolian sand. The results of grain-size analysis...
demonstrate that most samples are dominant by coarse fractions with particle diameters greater than 63 μm (Figure 1B). The reader is referred to Peng et al. (2022) for further information on the samples.

Raw samples were processed with the standard procedure (see Peng et al., 2022 and reference therein) to extract the 90–125 μm (or 63–90 μm, i.e., sample TDN6-4) quartz fractions which were subsequently contained in the inner part (four to five mm in diameter) of the discs for OSL measurements. Post-IR OSL signals were measured with a Risø-TL/OSL-DA-20 reader equipped with IR LEDs (870 nm, 48 mW/cm²) and blue LEDs (470 nm, 48 mW/cm²) to suppress the contribution of feldspar luminescence (e.g., Banerjee et al., 2001). Post-IR OSL signals were collected at 130°C for 40 s (with 400 channels). The preheat temperatures before the natural and regenerative OSL measurements were 260 and 220°C, respectively. The test dose used for sensitivity correction was 7.9 Gy throughout the measurements. D_e measurements were conducted using the single-aliquot regenerative-dose (SAR) (Murray and Wintle, 2000) and the standardized growth curve (SGC) (Roberts and Duller, 2004) methods. SAR D_e was determined by a full protocol with one natural cycle and six regenerative cycles. SGC D_e was determined by projecting the sensitivity-corrected natural OSL signal (L_n/T_n) onto a pre-determined SGC. OSL data analysis was performed using the R package “numOSL” (Peng et al., 2013; Peng and Li, 2017).

Numerical simulations were performed to generate heterogeneously-bleached D_e distributions (e.g., Peng, 2021) so as to validate the bleaching performance of the measured multi-grain aliquots. Single-grain OSL sensitivities were simulated from the empirical distribution of a measured sand dune sample according to the method of Rhodes (2007). OSL signals were generated using a pre-determined dose-response curve (DRC) described by a single saturating exponential function (e.g., Li et al., 2017). The heterogeneous bleaching process of the single-grain quartz OSL was simulated by assuming that the fast-component OSL signal decays exponentially with sunlight exposure duration with a bleaching rate of 0.4 s⁻¹ which allows the OSL signal to decay to less than 2% of its initial level after a bleaching duration of 10 s (Peng et al., 2020). This is consistent with the sunlight bleaching experiment work carried out by Godfrey-Smith et al. (1988) who predicted that 90% of the natural optical signal should be erased following a 10 s exposure to sunlight. The methodologies and terminologies used to simulate the baseline doses, baseline signals, residual signals, residual doses, burial doses, and natural doses were consistent with those of Peng et al. (2020). To synthetize multi-grain D_e distributions, a random sampling protocol (without replacement) was used to draw subsets from 1,000 simulated noise-free single-grain OSL datasets, and each subset containing OSL signals from N_a heterogeneously-bleached grains were superposed and noised to generate a “measured” multi-grain D_e value (and associated standard errors). The process was implemented repeatedly to generated “measured” multi-grain D_e distributions. The “measured” OSL signal was simulated by taking into account the counting statistics, instrument irreproducibility, and intrinsic over-dispersion (e.g., Li et al., 2017; Peng et al., 2020; Peng, 2021).

**RESULTS**

**Measured Results**

Typical natural OSL decay curves are presented in Figure 2, for samples TDN6-4 and TDN15-1. A detectable natural OSL signal is presented in certain aliquots of TDN6-4 but absent in all aliquots of TDN15-1. Figure 3A shows typical SAR D_e calculation for a sample (TDN15-1). Due to the low signal-to-noise ratios of the measured decay curves, the SAR D_e calculations were characterized by very large uncertainties. Figure 4 shows the variation of the SAR D_e with the sensitivity-corrected natural OSL signal (e.g., Li, 2001) for eleven out of twelve samples (except TDN33-1). It shows that for certain samples (such as TDN6-4, TDN15-1, TDN17-1, and TDN30-4) positive correlations are observed between D_e and L_n/T_n values.

We applied the SGC method to these young aeolian sediments to improve the precision of D_e determination and to rapid explore their potential burial dose distributions (e.g., Hu and Li, 2019; Yang et al., 2020). The common DRC used for SGC D_e calculation (i.e., Peng et al., 2022) is shown in Figure 3B and a comparison of SAR and SGC D_e estimates for eleven samples is shown in Figure 3C. The two different methods yield D_e estimates that are broadly consistent with each other after accounting for associated errors. The calculated SGC D_e distributions are shown in Figure 5 as radial plots (Galbraith, 1988). Since negative D_e values present in most SGC D_e distributions, we computed the SAR D_e values based on a linear extrapolation of the measured natural OSL signal.
distributions due to poor counting statistics, a linear transformation (rather than a logarithmic transformation) as suggested by Vermeesch (2009) was used to draw the radial plots. It demonstrates that the SGC De distributions fall into narrow ranges and most De values are within the two-sigma range. The final De estimates were determined using an unlogged version of the central age model (Galbraith et al., 1999). The max final De estimate was calculated as 1.09 ± 0.15 Gy (i.e., sample TDN6-4) and ten samples (i.e., TDN15-1, TDN15-2, TDN17-1, TDN18-1, TDN21-1, TDN21-2, TDN24-1, TDN24-2, TDN32-1, TDN33-1) yield De estimates ranging between -0.26 ± 0.05 Gy and 0.2 ± 0.23 Gy.

Simulated Results
Considering that each of the above measured multi-grain aliquots contains at least 200 quartz grains (i.e., according to Duller, 2008) and therefore the results may be influenced by the “averaging” effect which may obscure the results and the effect amplifies as the number of grains within an aliquots (Ng) increases (e.g., Wallinga, 2002; Rhodes, 2007; Buckland et al., 2019), we explored the possible influences of this effect on the resultant multi-grain De distributions measured from aeolian samples with weak OSL intensities by numerical simulation of heterogeneously-bleached dose distributions (e.g., Peng et al., 2020; Peng, 2021). The mean burial dose absorbed by the grains since their last exposure to sunlight (μq) was fixed as 0.1 Gy (i.e., close to the average CAM De determined in Figure 5), the mean baseline doses (μe) accumulated in the quartz grains prior to their last transport and depositional events was either 10 or 50 Gy, and the proportion of fully-bleached grains (p) was either 0.05, 0.5, or 0.95. The simulated De distributions with Ng values of 1, 10, and 200 are presented in Figures 6, 7, respectively, for two scenarios with μq values of 10 and 50 Gy.

We demonstrated in both scenarios that the standard errors of De values decrease dramatically while the CAM De estimates increase gradually as Ng increases (Figures 6, 7). In addition, in the cases of p = 0.05 and p = 0.5, the increase in CAM De estimates is more significant when Ng increases from 1 to 10 (compared to the situation of Ng increases from 10 to 200). By contrast, in the cases of p = 0.95, the increase in CAM De estimates is insignificant among Ng values of 1, 10, and 200. These demonstrate the non-linear variation of the “averaging” effect with p and Ng values. In both scenarios, the CAM De estimate decreases as p increases (Figures 6, 7). In the scenario of μq = 10 Gy, the single-grain CAM De estimate (Figure 6G) is consistent with multi-grain ones (Figures 6H,I) when p = 0.95. By contrast, in the scenario of μq = 50 Gy, the CAM De estimate increases slightly as Ng increases from 1 to 200 when p = 0.95 (Figures 7G–I). In addition, the CAM De estimates obtained from a smaller baseline dose are obviously lower than those obtained from a larger baseline dose; the maximum CAM De estimates are 2.22 ± 0.013 Gy and 10.37 ± 0.047 Gy, when μq = 10 Gy and μq = 50 Gy, respectively. These results demonstrate the strong influences of the baseline doses and the proportion of fully-bleached grains on the simulated dose distributions (Peng et al., 2020).

DISCUSSION
A positive correlation was identified between ln/Tn and corresponding SAR De in several samples (Figure 4), suggesting that these multi-grain aliquots might have been influenced by heterogeneous bleaching (e.g., Fan et al., 2013). However, we noted that it is improper to diagnose them as heterogeneously-bleached samples based solely on the ln/Tn versus De plot. For example, although the natural OSL
The intensity of sample TDN15-1 is close to the background level (Figure 2B), an obvious positive relationship is observed between Ln/Tn and De (Figure 4B), suggesting the diagnosis method is inapplicable. This may because 1) the huge uncertainty of the calculated SAR De caused by poor counting statistics and 2) the “averaging” effect arising from the multi-grain results discount the usefulness of the Ln/Tn versus De plot. In the first situation, Ln/Tn and De values have large uncertainties and in the second...
situation, an increase of $D_e$ as a function of $L_0/T_n$ may merely result from the superposition of signals originated from different grains. Wallinga (2002) demonstrated that a correlation between natural OSL and associated $D_e$ should only be expected for heterogeneously-bleached multi-grain samples when the OSL sensitivity of individual grains is similar. In addition, Fan et al.
(2013) suggested that the Ln/Tn versus Dn plot is only applicable for the portion of the plot containing only positive Dn values. An alternative method for bleaching degree diagnosis is inspecting the Dn distribution, that is, tight Dn distributions are expected for undisturbed and fully-bleached samples (e.g., Olley et al., 2004; Arnold et al., 2009). The Dn distributions obtained using the SGC method demonstrate small between-aliquot variations and the resultant CAM Dn estimates are very small (Figure 5). However, it has been pointed out that the detection of heterogeneous bleaching based solely on this method may fail if a large number of grains are presented within an aliquot (e.g., Wallinga, 2002; Duller, 2008). Accordingly, it is best that the bleaching degree of OSL signals of multi-grain aliquots can be assessed using multiple methods.

Considering the abovementioned concerns on the detection of heterogeneous bleaching based on the multi-grain results presented here, we further applied a simulation approach to validate the bleaching degree of these samples. When a grain number of 200 (i.e., the expected minimum grain numbers for the measured aliquots of Figure 5) and a small baseline dose (10 Gy) were applied, the CAM Dn calculated using the simulated multi-grain aliquots were 2.22 ± 0.013 Gy (Figure 6C), 1.24 ± 0.011 Gy (Figure 6F), and 0.2 ± 0.0068 Gy (Figure 6I), respectively, if the proportion of fully-bleached grains are small (5%).

FIGURE 6 | Dn distributions simulated using a burial dose of $\mu_\alpha = 0.1$ Gy and a baseline dose of $\mu_q = 10$ Gy, for different proportions of fully-bleached grains ($p$) and different numbers of grains contained in an aliquot ($N_g$). Each subplot consists of 1,000 Dn values. The dashed lines indicate the two sigma range of the distribution.
When a grain number of 200 and a relatively large baseline dose (50 Gy) were applied, the CAM De estimates were 10.37 ± 0.047 Gy (Figure 7C), 4.76 ± 0.029 Gy (Figure 7F), and 0.62 ± 0.011 Gy (Figure 7I), respectively. The measured De distributions containing both positive and negative De values and tight dose distributions (Figure 5B–I) are more similar to the one of Figure 6I simulated with a large proportion of fully-bleached grains and a small baseline dose. In addition, a small baseline dose and a proportion of fully-bleached grains of 50% (i.e., Figure 6F) yield a CAM De similar to the measured sample TDN6-4 (Figure 5A). These results validate that the measured multi-grain aliquots of Figure 5 (except TDN6-4) had small residual doses before the last exposure to sunlight and most of their grains (at least 95%) were fully bleached before deposition. Yang et al. (2020) reached a similar conclusion for their coarse-grained aeolian samples collected from the middle Hexi Corridor to the west of the Tengger Desert.

The bleaching of optically sensitive electrons within a quartz grain depends on both the transport medium and the deposition mechanism. The distance or time duration of transport (Spooner et al., 2001; Singhvi and Porat, 2008) and the deposition process (Rhodes, 2011; Fan et al., 2013) are two major factors influencing the bleaching degree of aeolian sediments, that is, a longer transport distance and a slower deposition rate enable higher...
degree of bleaching. Since most of the investigated aeolian samples were collected along the margin of the Tengger Desert (with relatively short transport distance), transport distance should not be a critical factor responsible for the good bleaching performance. A possible mechanism prompting a high degree of bleaching is that these near-surface samples have experienced strong wind-driven erosion/working processes before their final deposition. This is likely to occur in relatively high-energy environments characterized by intermittent strong winds such as the Tengger Desert (e.g., Fan et al., 2002; Lv et al., 2009; Zhang et al., 2014). The extremely high volume abundances in the uppermost part of the grain-size distributions (see Figure 1B) suggest that almost samples acquired their sorting characteristics in a high-energy environment. An already halted/deposited quartz grain will have a chance to be exposed to sunlight if it subsequently suffers from at least one cycle of erosion/working, which explains why the measured multi-grain D_S distributions can be successfully reproduced by the simulation model fed with a small baseline dose. Rhodes (2011) emphasized the importance of total transport time and the repeated burst of movement interspersed with temporary shallow burial or halts on the bleaching of grains and pointed out that the last transport event before the final deposition is not necessarily the most important if the grain has been exposed for sufficient duration during previous movement/working. In addition, the negligible volume abundances of fine particles contained within almost aeolian samples (Figure 1B) suggest that the bleaching of these coarse grains might have not been severely influenced by the phenomena of aggregation (or the adhering of fine particles to coarser ones) (e.g., Derbyshire et al., 1998) which impedes the bleaching of aggregated grains by attenuating of sunlight during transportation.

**CONCLUSION**

The bleaching degree of multi-grain coarse quartz OSL signals from the margin of the Tengger Desert was investigated by both empirical analysis and numerical validation. The tight D_S distributions and small D_E values indicate that these multi-grain aliquots may have been fully bleached before deposition. A numerical modelling method is able to reproduce multi-grain D_E distributions similar to the measured ones only if the vast majority of the grains within an aliquot are fully bleached and the baseline dose is relatively small during the simulation. These results reassure us to strengthens the conclusion that most investigated samples are fully bleached before deposition, which may be explained by the wind-driven erosion/working of the already stopped near-surface sediments and/or the absence of severe aggregation of grains.

**DATA AVAILABILITY STATEMENT**

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

**AUTHOR CONTRIBUTIONS**

HM conceptualized the study, conducted the investigation and visualization, and wrote the original draft. JP conducted the investigation and visualization, performed the numerical simulation, and edited the manuscript. ZL conducted the investigation and visualization, and performed the formal analysis. TF edited and reviewed the manuscript.

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