GEOCHRONOMETRIA 38(3) 2011: 199-208
DOI 10.2478/s13386-011-0030-9

Available online at
www.springerlink.com

AN ASSESSMENT OF THE LUMINESCENCE SENSITIVITY OF AUSTRALIAN QUARTZ WITH RESPECT TO SEDIMENT HISTORY

KATHRYN E. FITZSIMMONS[1, 2]
[1] *Department of Human Evolution, Max Planck Institute for Evolutionary Anthropology,*
Deutscher Platz 6, D-04103 Leipzig, Germany
[2] *Research School of Earth Sciences, Australian National University,*
Canberra ACT 0200, Australia

Received 27 January 2010 Accepted 21 December 2010

Abstract: This study provides a preliminary systematic characterisation of OSL sensitivity, with respect to sediment history, of single grains of Australian quartz from a variety of source rocks and depositional contexts. Samples from two distinct lithologies and with relatively short modern sedimentary histories were compared in an examination of the influence of rock type on OSL sensitivity. Sediments derived from weathered sandstone were found to be brighter than those from metamorphosed schists, suggesting that sensitivity may be inherited from the source rock and its earlier sedimentary history. Secondly, quartz from the same source, but different modes of deposition, was compared to assess the effect on sensitivity of nature of exposure to light during the most recent bleaching event. Quartz grain sensitivity appears not to vary depending on the mode of sediment deposition, suggesting that the nature of exposure to light during deposition is less important in the sensitisation process. This study highlights the complexity and variety of natural sedimentary quartz, demonstrating the limitations of an investigation based solely on OSL sensitivity. Further systematic investigation into the physical, geological and geomorphological characteristics of sediments is proposed to better understand the mechanisms of luminescence sensitisation in quartz.

Keywords: Optically stimulated luminescence (OSL), luminescence signal sensitivity, sediment provenance, sediment history.

1. INTRODUCTION

Australian quartz is widely perceived to be inherently suitable for optically stimulated luminescence (OSL) dating. This perception has arisen largely from experimental investigations of the OSL signal characteristics of Australian aeolian sediments, associated with the development of the single-aliquot regenerative-dose (SAR) protocol (Murray and Roberts, 1998; Murray and Wintle, 2000; Wintle and Murray, 1999). In these and subsequent studies, Australian quartz samples were found generally to emit intense OSL signals and to respond well to the SAR protocol (Fitzsimmons *et al.*, 2010), in comparison with quartz from sedimentary systems in other parts of the world (e.g. Hülle *et al.*, 2010; Preusser *et al.*, 2006; Timar *et al.*, 2010). Australian quartz generally yields not only very intense OSL signals in terms of photon counts, but also demonstrates relatively high OSL sensitivity.

Highly sensitive samples are preferable for dating particularly young sediments with low accumulated doses (Pietsch, 2009), as well as older sediments (for example, using the proportionally dim thermally-transferred OSL signal; see Wang *et al.*, 2006), provided they pass the criteria for the relevant dating protocols. It is therefore of benefit to understand potential causes of sensitisation of quartz within the natural system, and to identify to what

---

Corresponding author: K. E. Fitzsimmons
e-mail: kathryn_fitzsimmons@eva.mpg.de

ISSN 1897-1695 (online), 1733-8387 (print)

degree source geology and crystal formation (Westaway, 2009) and sedimentary processes (Pietsch *et al*., 2008) influence sensitivity and can be used to predict the suitability of sediments for dating. This paper attempts an empirical assessment of the natural OSL sensitivity characteristics of single grains of Australian quartz, from various source rocks and depositional contexts with respect to their suitability for dating.

OSL sensitivity is the signal intensity per unit absorbed radiation dose. Whereas OSL intensity is a function of the amount of radiation exposure to the quartz since burial, sensitivity relates to the efficiency with which the absorbed radiation is transmitted as luminescence. Luminescence sensitivity arises from the efficiency of charge traffic between traps and luminescence (L) centres. The rate and quantity of charge traffic is determined by the absolute number of available traps and L-centres, as well as competition with non-luminescence (R) centres (Aitken, 1998 p.195; Zimmerman, 1971). Such characteristics relate to crystal formation and the presence of impurities (Aitken, 1985 p.41; Hashimoto *et al*., 1997), and hence the type of source rock (Westaway, 2009; Zheng *et al*., 2009). Experimental work on the thermoluminescence (TL) characteristics of quartz indicated that competition between L- and R-centres alters with subsequent exposure to temperature (e.g. Rhodes and Bailey, 1997; Vartanian *et al*., 2000), bleaching (e.g. McKeever, 1991; Wintle, 1985) and irradiation (e.g. Zimmerman, 1971). Since these processes are echoed in the natural world, it has been hypothesised that similar exposure within the natural environment also affects quartz sensitivity (e.g. Li and Wintle, 1992; Li and Wintle, 1991). Luminescence sensitisation of quartz must therefore be a product of the interplay between source lithology (Li *et al*., 2007; Westaway, 2009) and sediment history (Fitzsimmons *et al*., 2010; Pietsch *et al*., 2008; Preusser *et al*., 2006).

Sensitisation of quartz within natural sedimentary systems has been understudied relative to laboratory experiments. Until now, the generally high OSL sensitivity of Australian quartz has been assumed to be due to the typically long histories experienced by sediments on the continent, which cause sensitisation through repeated reworking and burial (Pietsch *et al*., 2008). However, there is also evidence that the nature of exposure immediately prior to the most recent burial event increases OSL sensitivity (Fitzsimmons *et al*., 2010). Comparison between different Australian quartz types has not yet been attempted, although inter-regional comparisons have been made between Australian and non-Australian quartz (Westaway, 2009).

The availability of single grain measurement techniques enables more accurate observations of OSL sensitivity characteristics than is achieved with single aliquots. Single grain measurements present the opportunity for a new empirical approach to understanding the relationship between sensitivity and geological context. This study takes a twofold approach to a preliminary assessment of natural OSL sensitisation. Firstly, samples from two distinct lithologies, and with relatively short sedimentary histories, are compared in an examination of the influence of rock type on OSL sensitivity. Secondly, samples from a mixture of source rocks and a variety of depositional contexts, and with relatively long sediment histories, are contrasted with each other and with the first set of samples. This second study elucidates the effect of the nature of exposure to light during the most recent bleaching event on sensitivity. In addition, it tests quartz sensitisation resulting from the amount of exposure to cycles of reworking and burial. The present study provides a preliminary assessment of the relationship between natural OSL sensitivity and source geology, and OSL sensitivity and mode of deposition. In doing so the complexity and variety within natural sedimentary quartz is highlighted, demonstrating the limitations of an investigation based solely on OSL sensitivity.

2. SAMPLES

Twenty samples were analysed in this study (**Table 1**). The samples were collected from four locations across southeastern Australia, and correspond to different source rocks and depositional processes.

For comparison of the influence of rock type on OSL sensitivity, samples were collected from Pleistocene sediments in the upper parts of two catchments – Pilot Creek (PC) and Black Mountain (BM) - in the highlands of southeastern Australia. Five fluvial samples were collected from terrace deposits at PC, a small ephemeral channel located approximately 100 km south of Canberra. These samples were collected less than 1 km from the head of the catchment, which comprises quartz-bearing schists (Richards and Collins, 2002). The sediments comprise clays and laminated sands, with one sample collected from a low energy swampy meadow unit and two from poorly sorted gravelly sands. Consequently, the PC samples may not have been completely bleached during deposition. These samples have been transported only a short distance from in situ weathered rock, and have therefore experienced a limited sedimentary history involving relatively few cycles of burial and reworking. Equivalent dose values of 65-155 Gy for these samples (**Table 1**) imply that these sediments have experienced at least one cycle of transport and burial. Five samples were collected from periglacial (four samples) and alluvial fan (one sample) sediments in a gully at BM in central Canberra. These sediments were also collected less than 1 km from the head of the catchment, which comprises quartz-rich Silurian sandstone turbidites (Strusz, 1971). These samples have therefore also experienced minimal cycles of burial and reworking, although their equivalent dose values (100-130 Gy; **Table 1**) indicate at least one cycle of exposure to sunlight. The periglacial sediments consist of scree-dominated small cobbles within a sandy clay

Table 1. *Summary of samples with respect to source geology and geological context, mode of deposition, approximate equivalent dose and sensitivity.*

Sample	Location	Geological context	Location within catchment	Mode of deposition	Approximate D_e (Gy)	% grains where χ >100 (cts/s/Gy)	% grains where χ >1000 (cts/s/Gy)
K2038	Pilot Creek	Schist	Head of catchment	Fluvial	75	38	0
K2039				Fluvial	95	41	0
K2040				Fluvial	65	29	0
K2041				Fluvial	155	44	0
K2042				Fluvial	80	27	0
K1931	Black Mountain	Sandstone	Close to source (head of catchment)	Periglacial	100	25	0
K1932				Periglacial	115	24	0
K1933				Periglacial	105	57	7
K1934				Periglacial	130	54	7
K2034				Alluvial fan	100	33	4
K2140	Lake Mungo	Variety of protoliths (Lachlan Fold Belt rocks)	Large catchment, distal to source	Aeolian	7.5	44	4
K2178				Aeolian	25	49	8
K1935	Lake George	Variety of protoliths (slate, sandstone, shale)	Mid-size catchment, <10 km from source	Aeolian	9	3	0
K1936				Aeolian	70	24	0
K1939				Aeolian	7.5	0	0
K1944				Aeolian	1.1	0	0
K1971				Lacustrine (mud)	60	13	3
K1985				Lacustrine (shoreface)	>10	0	0
K1995				Lacustrine (gravel)	80	5	0
K1998				Lacustrine (gravel)	85	25	0

matrix. The poorly sorted nature of this material, combined with deposition by colluvial processes, implies that these samples are the least likely to have been completely bleached prior to deposition of all samples studied. This hypothesis is supported by their observed dose distributions. The alluvial fan sample was collected from clast-supported sediments within an incised terrace. The nature of the sediments suggests debris flow as the dominant depositional process, and therefore the OSL signal may not have been completely bleached during deposition. In this respect the PC and BM sediments are comparable in terms of the nature of exposure to sunlight, number of cycles of transport and burial, and proximity to source rock.

In the second component of this study, the PC and BM samples are contrasted with sediments with comparatively longer sediment histories and different depositional contexts. Additional samples were collected from Pleistocene and Holocene sediments in two substantially larger catchments in southeastern Australia, Lake George (LG) and Lake Mungo (LM). Eight samples were collected from aeolian and water-lain (lacustrine and fluvial) sediments at LG, 50 km northeast of Canberra. LG has a closed catchment of approximately 800 km^2, with the lake occupying approximately 20% of the total area. The geology within the basin is a mixture of low grade metamorphosed slates and greywackes, quartz sandstone, shale, and granite (Coventry, 1976). More than 46 m of sediment has accumulated in the lake, and multiple shorelines imply that the lake occupied a much larger proportion of the catchment in the past (Coventry, 1976; Fitzsimmons and Barrows, 2010). Samples were collected from proximal aeolian sediments deposited immediately downwind from the 18 m (lake depth) shoreline to the north of the present lake, from shoreface sediments and low energy lake muds at the 18 m shoreline, and from high energy deep water lacustrine gravels at the southern end. The 18 m shoreline has been occupied multiple times in the past, and was most recently occupied during the late Holocene (Fitzsimmons and Barrows, 2010). Studies of the TL characteristics of lacustrine and alluvial fan quartz deposited within the lake basin suggest that luminescence signal sensitivity varied depending on whether fluvial or lacustrine processes dominated (Mortlock and Price, 1984). The size of the lake basin and relative distance from unweathered source rock, coupled with younger ages for the sediments sampled (1-85 Gy; **Table 1**), suggest that the LG sediments have undergone comparatively more cycles of reworking than those from PC and BM. Finally, two aeolian samples were collected from the transverse lunette dune adjacent LM in semi-arid southeastern central Australia, approximately 600 km west-northwest of Canberra. LM is a dry lake located within the very large (>1 000 000 km^2) Murray-Darling River catchment. The lunette sediments are ultimately derived from a variety of source rocks along the >1 000 km reach of the Lachlan River/Willandra Creek system, including the metamorphosed sediments and plutonic rocks of Ordovician and Silurian age which form the New England and Lachlan fold belts (Pell *et al.*, 2001). Given the scale of the catchment and the location of LM within it, these sediments can be assumed to have experienced the longest sedimentary history of the suite of samples studied here, involving repeated cycles of deposition and reworking from at least the Tertiary to the present (Pell *et al.*, 2001). Transport of these samples down the Lachlan River/Willandra Creek dominates the sedimentary history of these samples. However, the most recent depositional process is aeolian, and it is highly likely that the sediments were exposed to more than one aeolian event prior to the most recent deposition, since aeolian reworking is common in arid environments such as this (e.g. Fitzsimmons *et al.*, 2009).

It should be noted that since the LM and LG sediments are derived from a mixture of source rocks, the influence of geology (and quartz type) on sensitivity cannot be directly compared with the PC and BM samples. It is generally the nature of Australian sediments with long sediment histories to occur within very large catchments, which typically comprise multiple source lithologies.

3. SAMPLE PREPARATION AND OSL MEASUREMENT

Samples were collected in steel tubes from cleaned exposures, with the exception of the BM sediments which were collected as bulk samples at night under red light. All samples were processed under low-intensity yellow-orange light. All samples were processed by dilute HCl digestion, wet sieving to extract the 180-212 µm grain size range, removal of heavy minerals using 2.68 g.cm^{-3} density sodium polytungstate solution, and etching in 48% HF acid at room temperature for 100 minutes. The resulting purified quartz was then washed, dried, and re-sieved. Individual quartz grains were loaded onto a minimum of six anodised stainless steel discs containing a 10×10 grid of 300 µm diameter holes for single grain measurement.

OSL measurements were undertaken using an automated Risø TL-DA-15 reader with a single grain laser attachment. Optical stimulation was provided by a 10 mW 532 nm solid-state green laser beam, preceded by preheating to either 260°C or 220°C (determined from preheat plateau tests run on multiple grain aliquots of the samples), and infrared stimulation (IRSL) to assist with identifying the presence of feldspars (Duller, 2003; Wintle and Murray, 2006). Sample irradiation was undertaken using a calibrated ^{90}Sr/^{90}Y beta source (Botter-Jensen *et al.*, 2000). Luminescence signals were detected by EMI 9235QA photomultiplier tubes with 7.5 mm Hoya U-340 filters (Botter-Jensen, 1997). Measurements were undertaken using the SAR protocol of Murray and Wintle (2000; 2003), incorporating a test dose of approximately 5 Gy following measurement of the post-IR stimulated natural and regenerated OSL signals for all samples. The sensitivity of individual grains was calculated from the OSL signal arising from the test dose immediately following measurement of the natural signal and quantified in counts/second/Gy. Test dose sensitivity following each of the six regenerative dose cycles was also calculated.

Single grain selection criteria

Single grain analyses arguably more reliably determine the age of a sample by identifying incomplete bleaching and post-depositional mixing of sediments, along with the rejection of grains unsuitable for dating (Duller, 2008). For the purposes of this study, single grain measurements also enable more reliable characterisation of quartz OSL signal and sensitivity characteristics of different samples, than can be obtained from single aliquot measurements where the combined OSL of multiple grains may obscure true sensitivity data (e.g. Fitzsimmons *et al.*, 2010; Zheng *et al.*, 2009).

Stringent rejection criteria were applied to the measurement data similar to the protocol suggested by Jacobs *et al.* (2003). Grains were accepted for analysis only if they were observed to emit sufficient OSL with rapid signal decay, produced an exponential dose-response curve, recycled within 20% of unity, and did not exhibit IRSL. OSL signals were integrated using channels 5-10, with counts from the final 10 measured channels taken as background for subtraction.

4. RESULTS

OSL signal

Representative natural luminescence decay curves for individual grains from four samples are shown in **Fig. 1**. **Fig. 1a** compares fluvial samples from PC (K2038; ~75 Gy) and BM (K2034; ~100 Gy). **Fig. 1b** shows the OSL decay curves for two aeolian samples from LM (K2178; ~25 Gy) and LG (K1935; ~9 Gy). The decay of all samples is rapid, with in excess of 50% loss of signal per second, but does not correspond to a single exponential function. This behaviour is not unexpected (as discussed in Wintle and Murray, 2000) and indicates either that more than one electron trap is contributing to the luminescence signal, and/or that signal efficiency is not entirely constant during stimulation (Aitken, 1998; p.26). Previous work on the Linearly Modulated OSL (LM-OSL) signals of samples from LG (Fitzsimmons *et al.*, 2010) supports this interpretation, suggesting that although the fast component OSL signal dominates, other components (such as the S2 slow component of Singarayer and Bailey, 2003) may be contributing to the overall signal. The background signal for the PC sample K2038 is proportionally highest out of all of the samples and may also be attributable to additional components beyond the fast component. The likely existence of more than one signal component contributing to the total OSL signal has implications for the use of the total OSL signal in assessing natural sensitivity. It nevertheless should be noted that the fast component represents >99% of the total signal for the samples analysed by LM-OSL.

Signal intensity varies between regions and different depositional contexts, even when differences in D_e are taken into account. This appears to relate to variations in

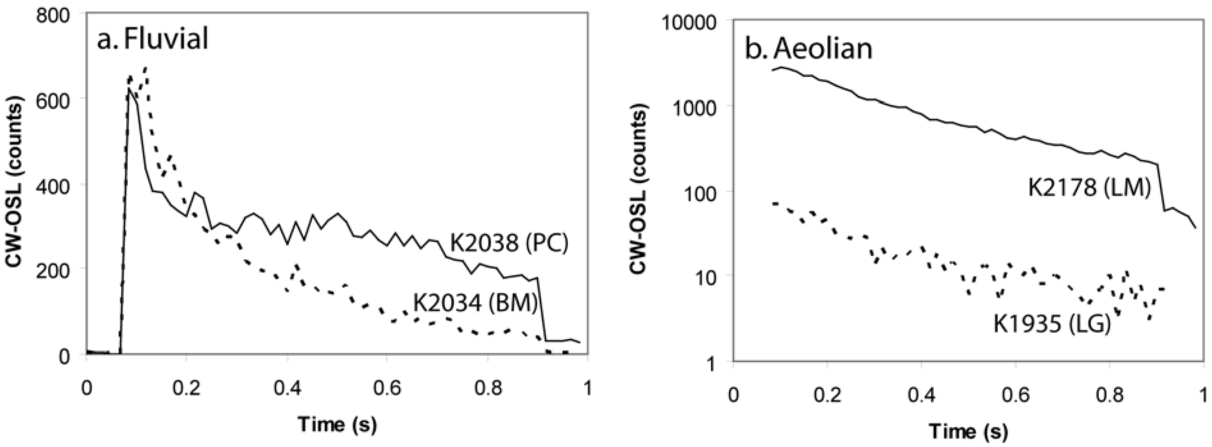

Fig. 1. *a) Natural OSL decay of fluvial samples (PC: Pilot Creek; BM: Black Mountain). b) Natural OSL decay of aeolian samples (LM: Lake Mungo; LG: Lake George). Note the differences in vertical scale (logarithmic scale used for b).*

sample sensitivity, discussed in the section on OSL sensitivity. Although it is important to note that sample intensity is dependent both on sample sensitivity and its age, irrespective of the differences in sample D_e, it is evident that the aeolian samples from LM are at least an order of magnitude more sensitive than both of the (older) fluvial samples, as well as the aeolian sample from LG.

The degree of bleaching of the samples and the corresponding D_e distributions are beyond the scope of this paper to discuss. However, it should be noted that the aeolian samples from both Lakes Mungo and George generally produce single D_e populations. The samples from BM and PC are characterised by wide D_e distributions, most likely attributable to incomplete bleaching and variations in microdosimetry (e.g. Lomax *et al.*, 2007). Lacustrine sediments from LG exhibit evidence of incomplete bleaching. Consequently the D_e values given in **Table 1** are approximate only (D_e values for LG samples K1935, K1939 and K1944 are discussed in Fitzsimmons and Barrows, 2010). All samples appear to be suitable for dating using the SAR protocol, based on the single grains which passed selection criteria. Selected samples analysed for dose recovery using both sunlight and laboratory bleaching yielded results close to unity.

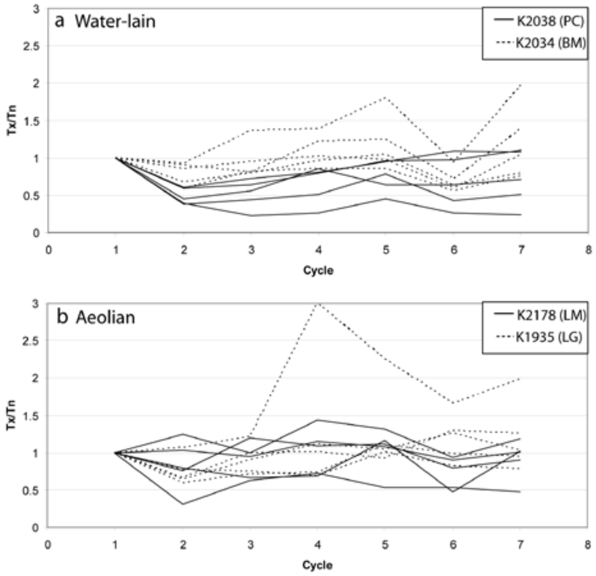

Fig. 2. *a) Test dose sensitivity change across regenerative cycles of the SAR protocol normalised to the first test dose response (T_n) obtained after measurement of the natural signal, for five representative grains each from fluvial samples K2038 (PC) and K2034 (BM). b) Test dose sensitivity change across cycles of the SAR protocol normalised to the first test dose response (T_n) obtained after measurement of the natural signal, for five representative grains each from aeolian samples K2178 (LM) and K1935 (LG).*

Sensitivity change

Change in sample sensitivity during the SAR protocol is monitored by administering a small test dose after each regenerative dose cycle (Murray and Wintle, 2000). A test dose of approximately 5 Gy was administered to all samples. **Fig. 2** shows the sensitivity change across regenerative cycles of the SAR protocol for five representative grains each from two fluvial (**Fig. 2a**) and two aeolian (**Fig. 2b**) samples from different regions. With the exception of one grain each from LG and BM (samples K1935 and K2034 respectively), the magnitude of sensitivity change for all samples remains within 50% of the first test dose response obtained after measurement of the natural signal (T_n). Overall, sensitivity change appears to be predominantly grain dependent, although the sensitivity of PC grains generally decreases from the natural, whereas BM quartz generally increases in sensitivity. The aeolian samples (derived from multiple rock sources) do not appear to exhibit any consistent pattern with successive regenerative dose cycles. Since the fluvial samples are each derived from single lithologic sources, one might hypothesise that the contrasting trends of test dose sensitivity change occur as a function of quartz characteristics inherited from the source rock. However, a substantially larger sample size and further testing is recommended to test this hypothesis further.

5. OSL SENSITIVITY

Substantial variation in sensitivity between samples, and between grains from individual samples, can be observed. The measurement of samples from different source rocks (region) and depositional context, using large numbers of grains (>600), aims to provide a systematic approach for assessing OSL sensitivity characteristics and to eliminate bias towards outlying anomalous grains.

The sensitivity of grains within each sample was classified by relative brightness (**Table 1**). Grains were classified as "bright" and "very bright" when sensitivity exceeded 100 and 1000 cts/s/Gy respectively, and the proportion of such grains was calculated as a percentage of the total. **Fig. 3a** illustrates the proportion of highly sensitive grains in the fluvial samples from PC and BM. The proportion of bright grains within the PC samples varies between 27 and 44%. Of the one fluvial sample from BM is represented, 33% of its grains are classified as bright, which is comparable to the PC samples. However, with the exception of the LG samples, bright grains represent between 25-57% of the total for the BM, PC and LM quartz, which suggests that no substantial conclusions can be drawn regarding proportion of bright grains and source lithology. **Fig. 3b** shows the proportion of bright grains for different depositional contexts from the LG samples. These data, however, are highly variable within each classification, suggesting that the proportion of bright grains does not depend on the mode of deposition, although it is interesting to note that no bright or very bright grains are present in the shoreface-deposited sample. Samples from LM are proportionally brighter than aeolian quartz from LG (**Fig. 3c**). This may reflect sensitisation through a greater number of cycles of reworking and burial. The highest proportion of very bright grains occurs within the BM and LM samples. Although the two sets of samples cannot be directly compared, the fact that the BM quartz contains some of the brightest grains observed in this study (**Table 1**) suggests that the proportion of bright grains is not entirely dependent on the length of time spent within the modern sedimentary system, and may also be inherited from the source rock.

The relationship between test dose sensitivity and source lithology for the fluvial samples from PC and BM is shown in **Fig. 4a**. There is substantial overlap between samples from the two sites, although several very bright grains are present in the BM sample compared with quartz from PC. **Fig. 4b** shows the same relationship, but with all of the data (not just fluvial) from BM. In this case the BM samples appear to be substantially more sensitive on average than those from PC, and contain a comparatively larger number of bright grains, particularly in the periglacial samples. The data from **Fig. 4b** suggest the possibility of a relationship between source lithology and sensitivity.

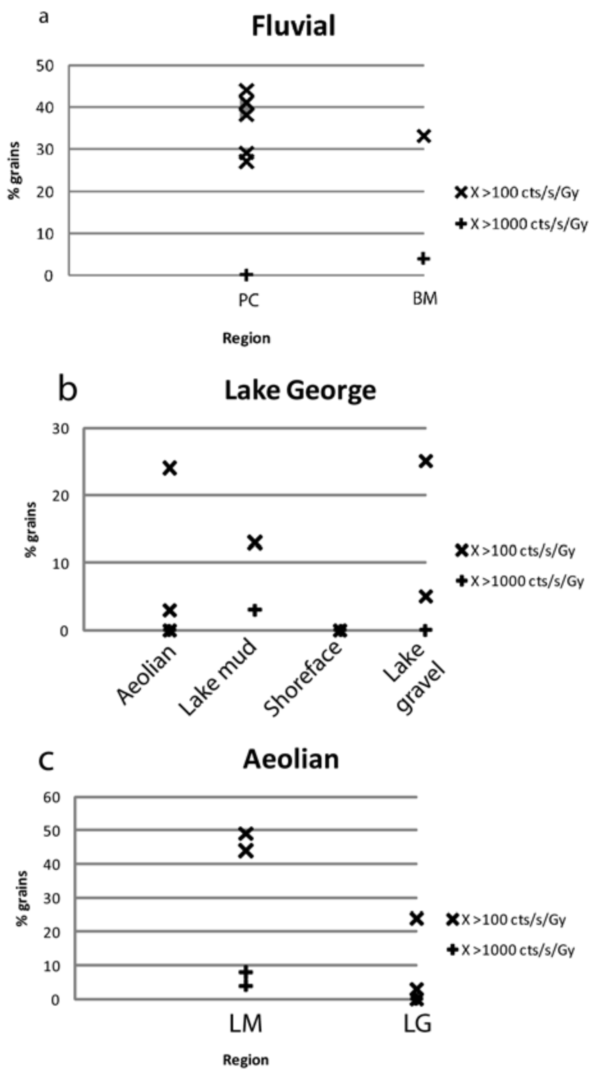

Fig. 3. *Proportion of bright (>100 cts/s/Gy) and very bright (>1000 cts/s/Gy) grains in a) fluvial samples from PC and BM, b) quartz from different depositional contexts at LG, and c) aeolian samples from LM and LG.*

Fig. 4b shows the relationship between test dose sensitivity and region for the aeolian sediments from LM and LG. Although it is difficult to compare sediments from LM and LG directly, sediments from LG nevertheless appear to be the least sensitive of the regions studied here. LM quartz is on average one order of magnitude brighter than the LG sediment.

Fig. 4c illustrates the relationship between test dose sensitivity and region for different depositional contexts for the LG samples. It is clear from this figure that there is wide variability in sensitivities between sediments from different depositional regimes, and that very low intensity grains occur for all modes of deposition. It is less clear whether average sensitivity varies systematically depending on depositional context. On average, the LG aeolian samples are the most sensitive, however bright grains are nevertheless also present in the lake muds and gravels. Grains deposited at the shoreface are noticeably the least sensitive. This latter result, compared with the sensitivity distributions for the other lacustrine sediments, is unexpected since there ought not to be a substantial difference in environmental conditions potentially influencing sensitisation for these three depositional modes.

6. DISCUSSION

This paper arose from the relative dearth of literature systematically investigating the naturally occurring OSL characteristics of sediments as they relate to source geology, mode of deposition and sedimentary history. This study represents a preliminary assessment of OSL sensitivity characteristics based on single grain data. The results presented here suggest that OSL sensitisation of quartz results from a complex interplay of factors including source geology and mode of deposition, and the potential for sensitivity inheritance from previous sediment histories.

All samples yield sufficient proportions of acceptably luminescent grains to make single grain analysis viable, and appear to be suitable for OSL dating using the SAR protocol. The fundamental suitability of these Australian samples for dating holds, irrespective of variations in OSL sensitivity and signal intensity.

Influence of source geology on quartz sensitivity

The hypothesis that quartz sensitisation increases with increasing time within the sedimentary system underpins the assumption that Australian quartz is highly sensitive compared with sediments from other parts of the world. The Australian continent is dominated by landscapes which have experienced long sediment histories, and recent investigations into the natural OSL sensitivity of Australian quartz support this hypothesis (Fitzsimmons *et al.*, 2010; Pietsch *et al.*, 2008). The observations made as part of this study, however, suggest that the relationship between sensitivity and length of time within the sedimentary system is not so straightforward.

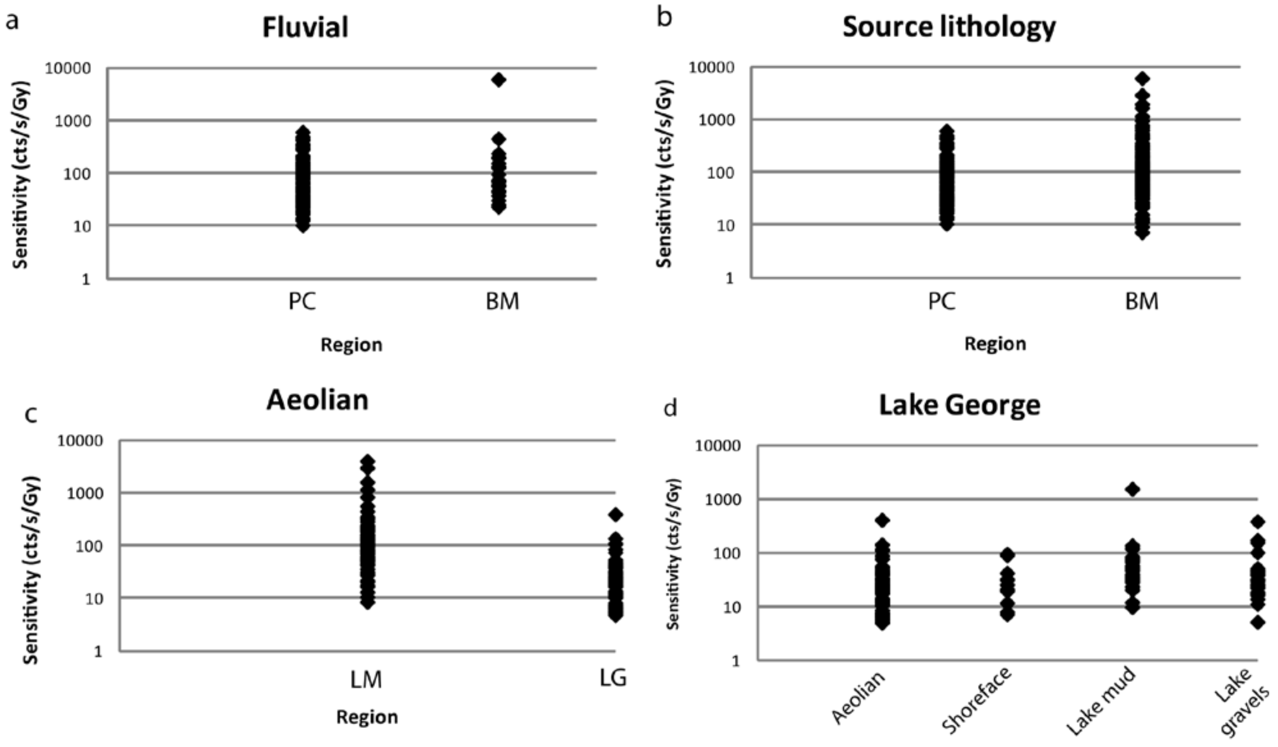

Fig. 4. *a) Plot showing relationship between luminescence sensitivity and region for all fluvial grains from PC and BM. b) Plot showing relationship between luminescence sensitivity and region for all grains (including periglacial samples) from PC and BM. c) Plot showing relationship between luminescence sensitivity and region for aeolian samples from LM and LG. d) Plot showing relationship between luminescence sensitivity and mode of deposition for samples from LG. Note logarithmic scale on y-axis for all graphs.*

Firstly, sensitivity change does not appear to vary systematically with source geology or depositional context, although grains from single samples tend to exhibit similar patterns of sensitivity change relative to one another. Interestingly, sensitivity change across the SAR cycles is greater in the BM sample relative to the one from PC (**Fig. 2a**). This latter observation may indicate the potential for inheritance of intrinsic sensitivity characteristics from the source rock, and therefore quartz type. Further work, involving more samples and more grains from each sample, is required to test this hypothesis.

Comparison of OSL sensitivity with respect to source region shows that the samples from PC are less sensitive on average compared with the BM sediments. The sensitivity of the latter is comparable with the LM samples, despite the fact that the BM periglacial and alluvial quartz has experienced a comparatively limited sedimentary history in recent (Quaternary) times, and taking caution with such a comparison. Since the BM quartz is derived from Silurian-age sandstone, it is likely that BM quartz sensitivity was inherited from the previous (pre-Quaternary) sedimentary history. By comparison, the PC samples are derived from metamorphosed schists. Therefore the BM quartz has effectively experienced two sets of sediment histories and potential sensitisation compared with that from PC. Furthermore, the BM Silurian sandstone is ultimately derived from a variety of sources compared with the more consistent formation of quartz within the PC source schists. While these differences in quartz history appear to have influenced quartz sensitisation, it is also possible that they influenced the amount of sensitivity change during SAR cycles as observed above.

Of the suite of samples from the regions derived from mixed source rocks but with longer sediment histories (LG and LM), the quartz from the LM lunette dune is substantially more sensitive. The intrinsic brightness of the LM sediments may be explained by these samples having undergone many more cycles of reworking and burial compared with the other sediments, and is consistent with a model of increasing sensitisation over extended periods of time within the sedimentary system.

It is worthwhile noting that the comparatively high sensitivity of single grains of quartz from BM relative to that from LG contradicts observations for the same samples measured using multiple grain aliquots in a previous study (Fitzsimmons *et al*., 2010). This highlights the need to use single grain measurements for investigating OSL characteristics.

Relationship between depositional context and sensitisation

The use of single grain measurements enables the proportion of anomalously bright grains in samples from different contexts to be quantified. The proportions of bright and very bright grains do not exhibit distinctive or systematic variation with respect to source rock or depositional context (**Fig. 3**). The one exception to this conclusion is the shoreface-deposited sample from LG, which contains no bright grains compared with its aeolian and lacustrine counterparts from the same basin (**Fig. 3b**). There is no obvious mechanism for this behaviour. However it should be noted that since the LG samples are derived from a mixture of different source rocks, and it is possible that the source of the shoreface quartz differs from that for the other samples.

There appears not to be a clear relationship between depositional context and OSL sensitivity for the LG sediments. On average, the LG aeolian sediments are the brightest, however water-lain muds and gravels also contain bright and very bright grains (**Fig. 4d**). This observation contradicts the hypothesis made by Li and Wintle (1992; 1991) that the duration and intensity of pre-burial bleaching influences the luminescence characteristics of a sample, based on the assumption that aeolian sediments experience generally longer exposure prior to deposition than water-lain material. The wavelength of illumination has also been proposed to affect sensitisation (McKeever, 1991). This may play a role in the lower average sensitivity of water-lain sediments, yet does not account for the presence of occasional bright grains within these sediments. Grains deposited at the shoreface are noticeably the least sensitive. As discussed above, there is no clear explanation for this result, since there ought not to be a substantial difference in environmental conditions potentially influencing sensitisation for the shoreface, lacustrine muds and lake gravels. The most likely possibility is variation in the mixtures of source rocks for the different samples.

Limitations of study

The results of this study highlight the complexities involved in the sensitisation of natural quartz, and the limitations of an investigation based solely on single grain OSL signal characterisation. Specifically, OSL signal measurement comprises the signal arising from all L-centres present in the quartz. It is apparent from the non-exponential decay of the samples from this study, and LM-OSL characterisation undertaken on the same samples in previous work (Fitzsimmons *et al*., 2010), that more than one component is contributing to the OSL signal. Combined with this is the possibility that the multiple OSL components exhibit variable sensitivity within a single quartz grain. These characteristics cannot be characterised using OSL alone. Therefore, future investigations ought to incorporate additional measurement techniques such as TL or spectrometry to more reliably elucidate the natural sensitisation of quartz.

Nevertheless, this study yields several results which warrant further testing. In particular, it was noted that sensitivity change between the grains of individual samples throughout the SAR cycle is broadly similar in the single-source samples (BM and PC), and may relate to inheritance of sensitivity characteristics from the source rock. Furthermore, it is unclear whether the proportion of anomalously bright grains relates to source rock or sedimentary history. More samples and more grains from each sample are required to investigate whether there is systematic variation with respect to proportion of bright grains.

7. CONCLUSIONS

Measurements of the OSL sensitivity of single grains of Australian quartz from a variety of regions and depositional contexts suggest that natural sensitisation of quartz is a complex process dependent predominantly on the inheritance of luminescence characteristics from the source rock. The mode of deposition may also play a role, although this is unclear from the results of this study. There appears not to be a clear relationship between OSL sensitivity and length of time spent within the modern sedimentary system. Of the single source sediments from PC and BM, the brightest samples were found to be from BM. Since the BM quartz is derived from weathered sandstone, it is hypothesised that if the modern quartz sand inherited sensitivity characteristics from the source rock, then these characteristics may also relate to the much earlier sedimentary processes forming the protolith. Of the aeolian samples derived from a mixture of source rocks, the LM dune sediments are substantially brighter than aeolian material from LG, which has experienced a relatively shorter modern sedimentary history but is derived from different lithologies. Caution should therefore be made with the interpretation of such observations. The mode of deposition appears not to systematically influence the sensitivity of samples from within the LG basin, suggesting that the nature of exposure to sunlight does not play as important a role as source lithology in sensitisation. However, further systematic research into the sensitisation of quartz within the natural environment is clearly warranted.

ACKNOWLEDGEMENTS

Thanks to Ian Davis at Pilot Creek, Winderadeen Farm and Readymix Quarries at Lake George, and the Traditional Tribal Groups of the Willandra Lakes World Heritage Area (Barkanji, Mutthi-Mutthi and Nyeampa) and New South Wales Department of Environment and Climate Change (Mungo National Park) at Lake Mungo, for access to the sampling sites. Thanks also to Tim Barrows for assistance with sample collection at Pilot Creek, Black Mountain and Lake George, and to Tim Barrows and Daryl Pappin for sample collection at Lake Mungo. Thanks to Radu Ioviţă for assistance with fitting the OSL decay curves. The author is grateful for the constructive comments of two anonymous reviewers on the submitted manuscript. The majority of this work was undertaken while the author was a postdoctoral fellow at the Research School of Earth Sciences, Australian National University.

REFERENCES

Aitken MJ, 1985. *Thermoluminescence dating*. London, Academic Press: 359pp.

Aitken MJ, 1998. *An introduction to optical dating: the dating of Quaternary sediments by the use of photon-stimulated luminescence*. New York, Oxford University Press.

Bøtter-Jensen L, 1997. Luminescence techniques: instrumentation and methods. *Radiation Measurements* 27(5-6): 749-768, DOI 10.1016/S1350-4487(97)00206-0.

Bøtter-Jensen L, Bulur E, Duller GAT and Murray AS, 2000. Advances in luminescence instrument systems. *Radiation Measurements* 32(5-6): 523-528, DOI 10.1016/S1350-4487(00)00039-1.

Coventry RJ, 1976. Abandoned shorelines and the late Quaternary history of Lake George, New South Wales. *Journal of the Geological Society of Australia* 23: 249-273.

Duller G, 2008. Single-grain optical dating of Quaternary sediments: why aliquot size matters in luminescence dating. *Boreas* 37(4): 589-612, DOI 10.1111/j.1502-3885.2008.00051.x.

Duller GAT, 2003. Distinguishing quartz and feldspar in single grain luminescence measurements. *Radiation Measurements* 37(2): 161-165, DOI 10.1016/S1350-4487(02)00170-1.

Fitzsimmons KE and Barrows TT, 2010. Holocene hydrologic variability in temperate southeastern Australia: An example from Lake George, New South Wales. *The Holocene* 20(4): 585-597, DOI: 10.1177/0959683609356589.

Fitzsimmons KE, Magee JW and Amos K, 2009. Characterisation of aeolian sediments from the Strzelecki and Tirari Deserts, Australia: implications for reconstructing palaeoenvironmental conditions. *Sedimentary Geology* 218(1-4): 61-73, DOI 10.1016/j.sedgeo.2009.04.004.

Fitzsimmons KE, Rhodes EJ and Barrows TT, 2010. OSL dating of southeast Australian quartz: A preliminary assessment of luminescence characteristics and behaviour. *Quaternary Geochronology* 5: 91-95, DOI 10.1016/j.quageo.2009.02.009.

Hashimoto T, Katayama H, Sakaue H, Hase H, Arimura T and Ojima T, 1997. Dependence of some radiation-induced phenomena from natural quartz on hydroxyl-impurity contents. *Radiation Measurements* 27(2): 243-250, DOI 10.1016/S1350-4487(96)00115-1.

Hülle D, Hilgers A, Radtke U, Stolz C, Hempelmann N, Grunert J, Felauer T and Lehmkuhl F, 2010. OSL dating of sediments from the Gobi desert, Southern Mongolia. *Quaternary Geochronology* 5(2-3): 107-113, DOI 10.1016/j.quageo.2009.06.002.

Jacobs Z, Duller GAT and Wintle AG, 2003. Optical dating of dune sand from Blombos Cave, South Africa: II--single grain data. *Journal of Human Evolution* 44(5): 613-625, DOI 10.1016/S0047-2484(03)00049-6.

Li S-H and Wintle AG, 1991. Sensitivity changes of luminescence signals from colluvial sediments after different bleaching procedures. *Ancient TL* 9: 50-54.

Li S-H and Wintle AG, 1992. Luminescence sensitivity change due to bleaching of sediments. *International Journal of Radiation Applications and Instrumentation. Part D. Nuclear Tracks and Radiation Measurements* 20(4): 567-573, DOI 10.1016/1359-0189(92)90006-H.

Li S-H, Chen YY, Li B, Sun JM and Yang LR, 2007. OSL dating of sediments from deserts in northern China. *Quaternary Geochronology* 2(1-4): 23-28, DOI 10.1016/j.quageo.2006.05.034.

Lomax J, Hilgers A, Twidale CR, Bourne JA and Radtke U, 2007. Treatment of broad palaeodose distributions in OSL dating of dune sands from the western Murray Basin, South Australia. *Quaternary Geochronology* 2(1-4): 51-56, DOI 10.1016/j.quageo.2006.05.015.

McKeever SWS, 1991. Mechanisms of thermoluminescence production: some problems and a few answers? *Nuclear Tracks and Radiation Measurements* 18(1-2): 5-12, DOI 10.1016/1359-0189(91)90085-V.

Mortlock A and Price D, 1984. Unusual features of the thermoluminescence signal profile for sediments from beneath Lake George, New South Wales. *Ancient TL* 2: 10-13.

Murray AS and Roberts RG, 1998. Measurement of the equivalent dose in quartz using a regenerative-dose single-aliquot protocol. *Radiation Measurements* 29(5): 503-515, DOI 10.1016/S1350-4487(98)00044-4.

Murray AS and Wintle AG, 2000. Luminescence dating of quartz using an improved single-aliquot regenerative-dose protocol. *Radiation Measurements* 32(1): 57-73, DOI 10.1016/S1350-4487(99)00253-X.

Murray AS and Wintle AG, 2003. The single aliquot regenerative dose protocol: potential for improvements in reliability. *Radiation Measurements* 37(4-5): 377-381, DOI 10.1016/S1350-4487(03)00053-2.

Pell SD, Chivas AR and Williams IS, 2001. The Mallee Dunefield: development and sand provenance. *Journal of Arid Environments* 48(2): 149-170, DOI 10.1006/jare.2000.0751.

Pietsch TJ, 2009. Optically stimulated luminescence dating of young (<500 years old) sediments: Testing estimates of burial dose. *Quaternary Geochronology* 4(5): 406-422, DOI 10.1016/j.quageo.2009.05.013.

Pietsch TJ, Olley JM and Nanson GC, 2008. Fluvial transport as a natural luminescence sensitiser of quartz. *Quaternary Geochronology* 3(4): 365-376, DOI 10.1016/j.quageo.2007.12.005.

Preusser F, Ramseyer K and Schlüchter C, 2006. Characterisation of low OSL intensity quartz from the New Zealand Alps. *Radiation Measurements* 41(7-8): 871-877, DOI 10.1016/j.radmeas.2006.04.019.

Rhodes EJ and Bailey RM, 1997. The effect of thermal transfer on the zeroing of the luminescence of quartz from recent glaciofluvial sediments. *Quaternary Geochronology* 16(3-5): 291-298, DOI 10.1016/S0277-3791(96)00100-X.

Richards SW and Collins WJ, 2002. The Cooma metamorphic complex, a low-P, high-T (LPHT) regional aureole beneath the Murrumbidgee Batholith. *Journal of Metamorphic Geology* 20: 119-134.

Singarayer JS and Bailey RM, 2003. Further investigations of the quartz optically stimulated luminescence components using linear modulation. *Radiation Measurements* 37(4-5): 451-458, DOI 10.1016/S1350-4487(03)00062-3.

Strusz DL, 1971. Canberra, ACT and NSW - 1:250 000 Geological Series - Explanatory notes. Canberra, Australian Government Public Service.

Timar A, Vandenberghe D, Panaiotu EC, Panaiotu CG, Necula C, Cosma C and van den Haute P, 2010. Optical dating of Romanian loess using fine-grained quartz. *Quaternary Geochronology* 5(2-3): 143-148, DOI 10.1016/j.quageo.2009.03.003.

Vartanian E, Guibert P, Roque C, Bechtel F and Schvoerer M, 2000. Changes in OSL properties of quartz by preheating: an interpretation. *Radiation Measurements* 32(5-6): 647-652, DOI 10.1016/S1350-4487(00)00109-8.

Wang XL, Wintle AG and Lu YC, 2006. Thermally transferred luminescence in fine-grained quartz from Chinese loess: Basic observations. *Radiation Measurements* 41(6): 649-658, DOI 10.1016/j.radmeas.2006.01.001.

Westaway KE, 2009. The red, white and blue of quartz luminescence: A comparison of De values derived for sediments from Australia and Indonesia using thermoluminescence and optically stimulated luminescence emissions. *Radiation Measurements* 44(5-6): 462-466, DOI 10.1016/j.radmeas.2009.06.001.

Wintle AG, 1985. Sensitization of TL signal by exposure to light. *Ancient TL* 3: 16-21.

Wintle AG and Murray AS, 1999. Luminescence sensitivity changes in quartz. *Radiation Measurements* 30(1): 107-118, DOI 10.1016/S1350-4487(98)00096-1.

Wintle AG and Murray AS, 2000. Quartz OSL: Effects of thermal treatment and their relevance to laboratory dating procedures. *Radiation Measurements* 32(5-6): 387-400, DOI 10.1016/S1350-4487(00)00057-3.

Wintle AG and Murray AS, 2006. A review of quartz optically stimulated luminescence characteristics and their relevance in single-aliquot regeneration dating protocols. *Radiation Measurements* 41(4): 369-391, DOI 10.1016/j.radmeas.2005.11.001.

Zheng CX, Zhou LP and Qin JT, 2009. Difference in luminescence sensitivity of coarse-grained quartz from deserts of northern China. *Radiation Measurements* 44(5-6): 534-537, DOI 10.1016/j.radmeas.2009.02.013.

Zimmerman J, 1971. The radiation-induced increase of thermoluminescence sensitivity of fired quartz. *Journal of Physics C: Solid state physics* 4: 3277-3291.