The Holocene

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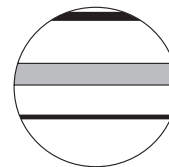
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What is This?

Holocene hydrologic variability in temperate southeastern Australia: An example from Lake George, New South Wales

Kathryn E. Fitzsimmons[1] and Timothy T. Barrows[2]

Abstract

Lake George is one of the largest freshwater lakes in Australia when full, and provides one of the most complete records of Quaternary sedimentation in the southeastern part of the continent. The lake is currently ephemeral, but sediments within the basin preserve evidence of multiple permanent and dry lake conditions in the past. We present an optically stimulated luminescence (OSL) chronology of recent lake shoreline sediments in order to reconstruct Holocene hydrologic variability at Lake George, providing past climatic context for the presently ephemeral lake conditions. The OSL chronology indicates three distinct periods of permanent lake conditions up to 15–18 m depth over the Holocene period, at approximately 10–8, 6–2.4 and 0.7–0.3 ka, with lower lake levels occurring in between those events. There appears to be a trend towards lake regression over this period despite relatively recent high lake levels. The chronology is broadly synchronous with comparable records of Holocene climatic variability across southeastern Australia. We also investigate the intrinsic luminescence characteristics of different sediment types as diagnostic tools, but these appear not to be appropriate in this context or form.

Introduction

Temperate southeastern Australia is one of the regions hardest hit by the drought that prevailed on the continent for more than ten years from 1997 to 2009. The Canberra region, in particular, has experienced record low precipitation, in the order of 10–20% reduction from the annual average since 2003 (Bureau of Meteorology, 2007). The reduced rainfall associated with the drought has effectively resulted in a change from sub-humid to semi-arid conditions in the Canberra region over this time period (Bureau of Meteorology, 2007). Lake George, an endorheic basin located approximately 50 km from Canberra and once mainland Australia's largest freshwater lake (Figure 1), has completely dried in response to this recent drought. The lake has intermittently filled to a shallow depth, and dried out, eight times during the period since European arrival 200 years ago (Jennings, 1981). The timing of these events matches that of historically documented droughts. The lake acts as a palaeo-rain gauge for the region, providing past context for present and future potential climatic conditions. Lake George therefore represents one of the most complete and valuable records of hydrologic variability as a response to drought and potentially increasingly dry conditions in southeastern Australia. However, regional hydrologic and environmental change over longer timescales – throughout the Holocene and Pleistocene – remains poorly resolved, lacking a comprehensively dated stratigraphic sequence.

Lake George has been the subject of several palaeoenvironmental studies by virtue of its long sequence of Quaternary lake sedimentation and multiple shorelines (Galloway, 1965; Coventry,
1976; Singh *et al*., 1981b; Singh and Geissler, 1985; Lees and Cook, 1991). Hydrologic change brought about by climatic variability is expressed in lake shorelines and associated dunes (Coventry and Walker, 1977). The lake has intermittently dried and filled to depths of up to 37 m several times during the late Quaternary period (Galloway, 1965; Coventry, 1976). However, the value of these early studies has been limited by radiocarbon dating using charcoal and undifferentiated carbonised wood fragments (Coventry, 1976; Coventry and Walker, 1977). Radiocarbon dates from sediment cores taken from the lake floor showed systematic contamination (Singh *et al*., 1981b; Singh and Geissler, 1985). Since the chronologies for lake-level change underpin interpretations of palaeoclimate based on runoff and evaporation within the basin (Galloway, 1965), inaccuracies in the dating limit our understanding of the system's response to palaeoenvironmental change.

This study seeks to address the existing limitations to reconstructing Holocene palaeoenvironmental change at Lake George.

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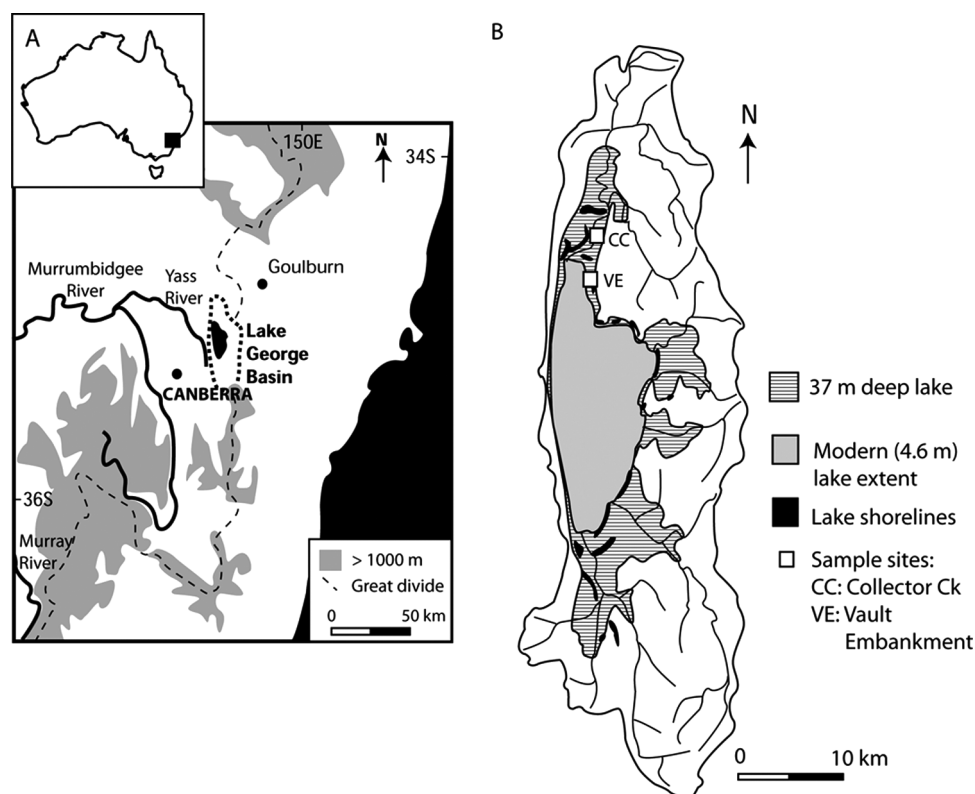Email: kathryn_fitzsimmons@eva.mpg.de

Figure 1. (A) Location of Lake George within the highlands of southeastern Australia. (B) Lake George catchment, showing the major streams flowing into the lake basin, significant lake shorelines and the projected extent of the lake at 37 m depth (adapted from Coventry, 1976)

We apply optically stimulated luminescence (OSL) dating to two stratigraphic sequences, located approximately 18 m and 11.5 m above the lake depocentre, respectively. These sequences represent the last phases of significantly high lake levels prior to present conditions and document changing hydrologic conditions through the Holocene. OSL dating circumvents many of the issues associated with the earlier radiocarbon chronology by directly dating when sediments were deposited (Aitken, 1998). We assess the luminescence behaviour of the samples with respect to depositional context and age. Finally, we construct a chronologic framework for hydrologic variability in southeastern Australia throughout the Holocene, and place the 1997–2009 drought conditions in the context of climate change.

Regional setting

Lake George is located in the southeastern Australian highlands (Figure 1), and lies within a hydrologically independent catchment approximately 800 km^2 in area (Singh *et al*., 1981b). The basin forms part of a horst and graben system (Strusz, 1971), which sits on the catchment divide between the large westward-draining Murray-Darling basin to the west, and smaller coastal catchments to the east (Figure 1A). The lake basin is flat, resulting in a large shallow water body when full. Inflow to the lake is dominated by precipitation directly onto the lake's surface, with the remaining inflow from short streams no greater than ~20 km in length (Figure 1B). Outflow is solely by evaporation (Jacobson and Schuett, 1979). Records of precipitation, evaporation and lake levels in the basin extend back as far as 1820 and show correlation between lake levels and the ratio of catchment rainfall to lake evaporation (Russell, 1887; Jennings, 1981). Lake George therefore

serves as an effective recorder of the relative intensity of rainfall versus evaporation in the region (Galloway, 1965).

The climate of the region is classified as temperate subhumid, with a mean monthly temperature range of 0–27°C and evenly distributed mean annual rainfall of 646 mm (Coventry, 1976). Since European arrival in the region 200 years ago the lake has never been greater than 7.3 m deep. 'Lake full' conditions are presently classified as 4.6 m depth. At this depth the lake occupies approximately 20% of the catchment area (Coventry, 1976). A number of shoreline ridges are preserved between 4 and 37 m above the lake depocentre (Coventry, 1976), indicating that the lake has been a much larger water body in the past than has existed during historical time. The most prominent shorelines lie at approximately 12 m, 18 m and 37 m above lake depocentre, and are complex features that indicate multiple periods of occupation at these depths (Coventry, 1976; Lees and Cook, 1991). It has been suggested that the lake would have breached the western escarpment of the basin at 37 m depth, resulting in overflow into a tributary of the Murrumbidgee River and therefore forming part of the major Murray-Darling basin catchment at that time (Coventry, 1976). The existing chronology indicates that this event took place well before the Holocene (Coventry, 1976; Coventry and Walker, 1977). The present 'lake full' shoreline at 4.6 m above lake depocentre is a subtle feature barely distinguishable from the flat lake floor. The lake is presently dry (2009) in response to the prevailing drought conditions that persisted from 1997 to 2009.

Sample sites

This study focuses on two stratigraphic sections at the northern end of Lake George, designated the Collector Creek and Vault
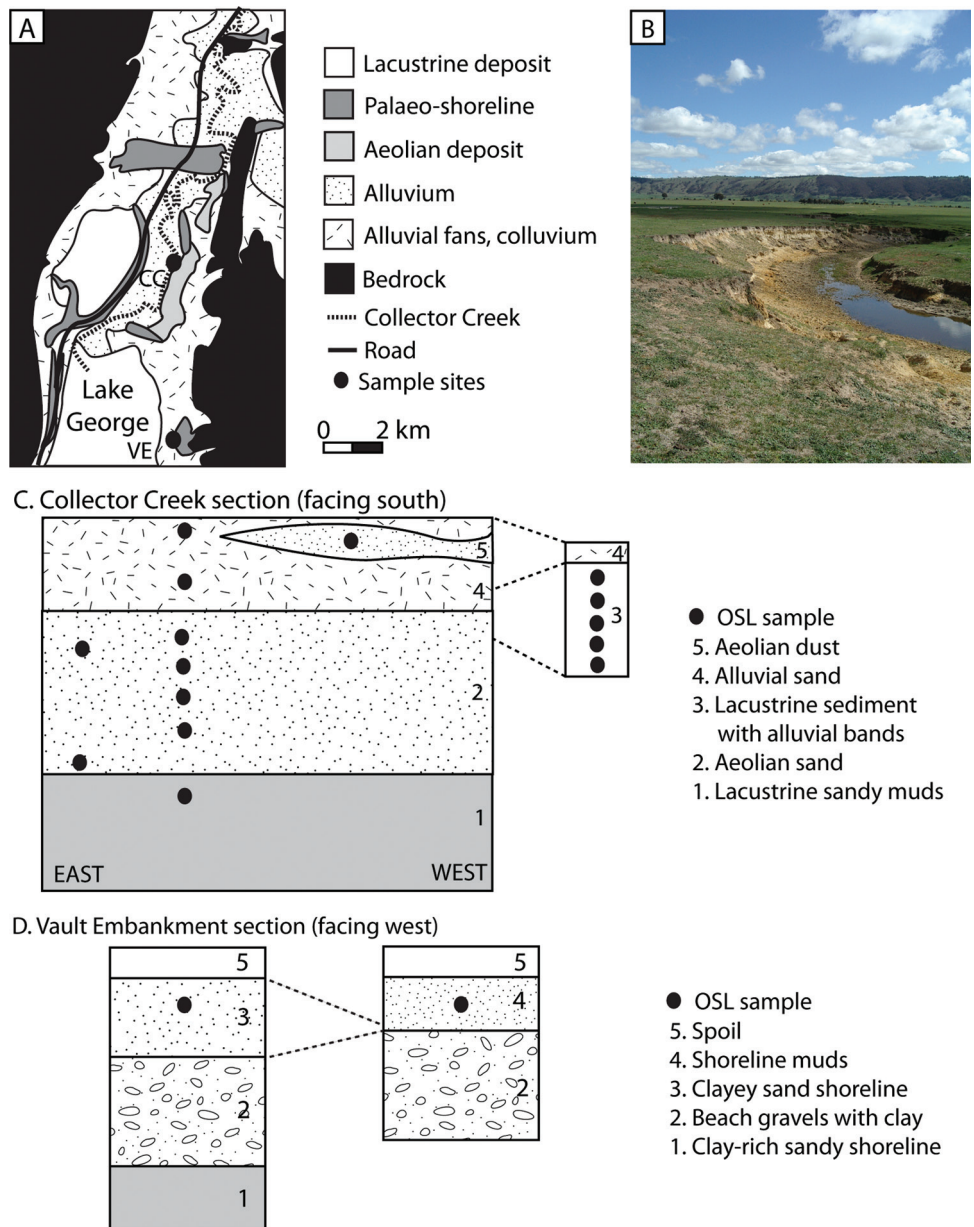
Figure 2. (A) Location of Collector Creek and Vault Embankment sample sites with respect to Lake George palaeo-shorelines. (B) Collector Creek sample site showing both banks of the Collector Creek, facing west towards the basin escarpment. Schematic diagrams of sample site stratigraphy, indicating OSL sampling strategy, at (C) Collector Creek, and (D) Vault Embankment

Embankment sites (Figure 1B). The two sections lie 15–18 m and 11.5 m above the lake depocentre, respectively, and are interpreted to represent the two most recent phases of high lake levels prior to the present ephemeral lake conditions.

The Collector Creek (CC) site is a cutting on the bank of Collector Creek (Figure 2A, B), the main inflow stream from the north of the catchment into the lake (Figure 1B). The CC site is located approximately 50 m west of a north–south trending sand ridge that marks the eastern expression of the 18 m shoreline embankment (Figure 2A). The lake depocentre lies to the south of the study site, although the lake basin slopes westward and southward from this point. Erosion by the Collector Creek has exposed an approximately 3 m high stratigraphic section on the southern bank and approximately 1 m of younger sand and mud sediments on the northern bank. The northern bank sits 1–2 m lower in the landscape than the southern bank, and the sediments that comprise it represent a more recent period of lake transgression to 15–18 m

depth than is preserved in the stratigraphy of the southern bank (see Section Results, Stratigraphy). The stratigraphy exposed on both sides of the creek indicates that the CC site has acted as the lake margin shoreface for multiple episodes of lake filling to 15–18 m depth (Figure 2C). However, the lake has not transgressed to a greater depth since its most recent occupation of the 18 m shoreline. We sampled the youngest sandy units on both sides of the creek (Figure 2B, C).

The Vault Embankment is an east–west trending shoreline approximately 5 km south of the Collector Creek site (Figure 2A). The Vault Embankment (VE) comprises two main beach ridges at 12.5–12.8 m and 11.5 m above the lake depocentre, and its location lakeward of another shoreline at the same altitude suggests that it is the most recent expression of a ~12 m deep lake phase (Coventry, 1976). The section studied lies on the lake basin edge of the lower beach ridge at approximately 11.5 m above the lake depocentre. It is a 0.7–1.4 m thick exposure of beach gravels and

Table 1. Summary of stratigraphy at Collector Creek and Vault Embankment sites

Stratigraphic unit	Sediment description	OSL samples collected
Collector Creek site		
1	Lacustrine sandy muds. Immediately underlying aeolian sand. Mottled red palaeosol	K1943
2	Well sorted, clean, medium aeolian sand. Weakly developed and spatially discontinuous palaeosol. Deposited immediately downwind from shoreface. Equivalent to Prairie Sands described by Coventry (1976)	K1935 K1939 K1940 K1941 K1942
3	Predominantly lacustrine sediment with alluvial bands. Lacustrine sediment grades from gravelly sandy clays (K1970) to sandy clays (K1969) and clays (K1966-8). Some laminae contain roots indicating shallow lake conditions, others are organic-rich, suggesting deeper lake. Alluvial bands contain sandy gravels. Unit indicates repeated lake transgression and regression at this site	K1966 K1967 K1968 K1969 K1970
4	Medium- to coarse-grained alluvial sand with minor gravels	K1937 K1938
5	Well sorted, clean, fine aeolian sand lens within alluvial sand (Unit 4). Probably derived from dry lake bed upwind and deposited as dust	K1944
Vault Embankment site		
1	Clay-rich sandy shoreline sediments	–
2	Beach gravels and illuviated clays. Indicative of lake margin at embankment	–
3	Dust-rich sandy shoreline sediments. Sequence fines upward	K2031
4	Fine mud and dust with minor sand. Contains roots indicating shallow lake margin conditions	K2030
5	Spoil from ploughing and small-scale quarrying	–

silt to fine sand-dominated shoreline sediments, overlain by ploughed soil and exposed by local quarrying (Figure 2D). The stratigraphic units for both sites are summarised in Table 1 and discussed in greater detail in Section Results, Stratigraphy.

Methods

Field methods

The stratigraphy of the CC section was mapped along approximately 25 m of the stream reach, with attention paid to the depositional type, sediment composition and texture of the younger units (Table 1). Fifteen OSL samples were collected from four points along the section: from three points on the southern bank and from one on the northern bank. This was undertaken in order to provide a full survey of the intercalating upper units, since the section preserves evidence of multiple episodes of lake shoreface occupation (Figure 2C). OSL samples were collected from aeolian, alluvial and lacustrine bands within alternating fluvio-lacustrine sediments (Table 1). There was no evidence of reworking or bioturbation within the fluvial and lacustrine units. No pedogenesis was observed within the fluvio-lacustrine sediments, but there was some weak soil development in the upper aeolian unit. The stratigraphy of the VE section was mapped at two points approximately 10 m apart, where the stratigraphy was clearly exposed (Figure 2D). Quarrying obscured the stratigraphy between the two points. Two OSL samples were collected, one from each of the two points.

OSL samples were collected by driving stainless steel tubes horizontally into cleaned, vertical surfaces. A microNomad sodium iodide portable gamma spectrometer, with a three inch crystal

detector, was then inserted into the hole created by each tube. Gamma counting was undertaken for 15 min for each hole. Additional bulk sediment was collected from around each sampling point for water content analysis.

Optically stimulated luminescence dating laboratory procedures

Samples were opened and processed under low intensity red and yellow-orange light to prevent resetting of the luminescence signal. OSL samples were processed using the method described in Fitzsimmons *et al.* (2007), with the 125–180 μm quartz size fraction isolated for equivalent dose (D_e) measurement. Only the sediment in the central section of the tubes was processed to minimise the risk of potential exposure to light during collection. Samples were subject to dilute hydrochloric acid digestion, sieving to isolate modal grain size, etching by immersion in 40% hydrofluoric acid for 100 min, density separation using sodium polytungstate solution of 2.68 g/cm^3 and final dry sieving. The resulting clean quartz grains were mounted onto the central 1 mm of 10 mm diameter stainless steel discs using silicone oil, for measurement of small aliquots comprising <100 grains, or mounted as single grains onto 10 mm diameter anodised aluminium discs each with 10 × 10 grids of 300 μm diameter holes.

In situ moisture content, required to account for dose rate attenuation, was calculated by weighing the raw and oven-dried weight of material from the ends of the tubes and bulk sediment collected from around the sample points. The average of these two values was taken as the final value, with a large uncertainty incorporated to allow for likely natural variation in moisture

content through time, ranging from drought to high lake levels at the sites.

Equivalent dose estimation

D_e measurements were undertaken both on single aliquots and single grains using automated Risø TL-DA-12 and TL-DA-15 readers, the latter with a single grain laser attachment. For single aliquot measurement, light stimulation was provided by clusters of blue light-emitting diodes (Bøtter-Jensen *et al*., 1999, 2000). Single grain light stimulation was provided by green and infrared lasers emitting at 532 nm and 830 nm, respectively (Bøtter-Jensen *et al*., 2000). The luminescence signal was detected by EMI 9235QA photomultiplier tubes with coated Hoya U-340 filters in both readers (Bøtter-Jensen, 1997). Irradiation was undertaken using calibrated $^{90}Sr/^{90}Y$ beta sources (Bøtter-Jensen *et al*., 2000).

D_e was determined using the single aliquot regenerative dose (SAR) protocol of Murray and Wintle (2000, 2003). Preheat plateau tests were undertaken on sample K1966 using preheat temperatures between 160°C and 300°C. Although some scatter was observed, variation was not attributed to preheat temperature. Preheat and cutheat temperatures of 260°C and 220°C, respectively, were therefore used. The SAR protocol was applied to 21 multiple grain aliquots of each sample. For the majority of samples, all 21 aliquots were considered acceptable on the basis of yielding sufficient OSL signal relative to background, simple exponential dose response curves, recycling within 10% of unity and low test dose errors. Single grain (SG) analysis of no fewer than 600 grains per sample was applied to three samples from CC section Units 2 and 5 (K1935, K1939, K1944). The central age model of Galbraith *et al*. (1999) was used to calculate the D_e for the CC samples. There was evidence of incomplete bleaching in the dose distributions of samples collected from the VE site and for sample K1936, indicated by a range of D_e values skewed towards younger ages representing better-bleached grains (Clarke, 1996; Colls *et al*., 2001; Olley *et al*., 1998). For these samples, the minimum age was used to calculate the D_e for these samples based on the leading edge of the dose distribution of accepted aliquots (e.g. Lepper and McKeever, 2002). There was no clear evidence of partial bleaching for sample K1944 (see Figure 3D), however single-aliquot analysis suggested sediment mixing, and therefore SG measurements were undertaken for this sample. The resulting SG age, derived from grains that passed the selection criteria, was substantially younger than that obtained from single-aliquot analysis. This was unexpected, but was attributed to contribution to the single-aliquot OSL signal of older, incompletely bleached grains of variable natural intensity. Sample sensitivity (measured as cts/s/Gy) both for the natural and first test dose signals was calculated for all aliquots and single grains with a detectable luminescence signal. Natural sample sensitivity was calculated by dividing the luminescence signal by the D_e for each individual aliquot or grain.

Dose rate determination

The beta component of the radiation dose rate was calculated using the concentrations of the radioactive isotopes U, Th and K and conversion factors of Adamiec and Aitken (1998). These were analysed using inductively coupled plasma mass spectrometry (ICPMS) for U and Th concentrations, and inductively-coupled plasma atomic emission spectrometry (ICPAES) for K concentration, at Genalysis Laboratories, Perth, Western Australia. *In situ* sodium iodide gamma spectrometry was undertaken at each sample point at the CC site and the data used for the gamma component of the dose rate. The modern water content of the samples was assumed to represent the long-term and spatial average, and was incorporated into dose rate calculations to correct for the attenuation of radiation by moisture. Beta dose attenuation was estimated using the values of Mejdahl (1979). The cosmic ray component of the dose rates was determined from sample depths and uniform values for sediment density and site altitude, latitude and longitude, following Prescott and Hutton (1994).

Results

Stratigraphy

Collector Creek site. The stratigraphy sampled for this study at the CC site comprises five units, summarised in Table 1 and shown schematically in Figure 4A. CC Units 1, 2, 4 and 5 are exposed in the southern bank of the creek and lie 15–18 m above lake depocentre. The interbedded fluvial-lacustrine sequence of Unit 3 is exposed in the northern bank, approximately 15 m above lake depocentre. Unit 3 palaeotopographically abuts the sediments of Units 1, 2 and possibly part of 4, which were cliffed by a preceding phase of erosion, possible by wave-cut action or by the Collector Creek. The contrasting sediments preserved on the northern creek bank, combined with the geomorphic context, indicate that Unit 3 represents a more recent lake transgression to 15–18 m depth than the lacustrine sandy muds of Unit 1. However, Unit 3 was most likely deposited prior to the deposition of the alluvial and aeolian sediments of Units 4 and 5, which sit higher in the landscape on the southern bank. We have shown Unit 3 as a separate horizon correlating to between Units 2 and 4 in the schematic stratigraphic diagram (Figure 4A).

The lacustrine sandy muds of Unit 1 represent the lowest stratigraphic unit at the CC site, and likely represent the deepest lake phase sampled in this study. This unit is interpreted as shallow (probably <1 m deep) lacustrine sediment, and therefore represents a 15+ m deep lake phase, possibly up to 18 m, although there is no clear evidence linking this unit with the 18 m embankment to the east. The grey-yellow sandy mud grades upwards into a mottled red palaeosol, which suggests a depositional hiatus between Units 1 and 2. Unit 2 is a well sorted, medium- to fine-grained quartz-rich massive aeolian sand horizon that increases in thickness towards the east to a maximum of 1 m. The description of this unit and its geographic location matches that of the Holocene-age Prairie Sand unit described by Coventry (1976). Unit 2 pinches out at the western (downstream) end of the CC site, which suggests that the Unit 2 sediments were deposited immediately downwind of the lake margin when the lake was ~15–18 m deep. There is no evidence of palaeosol development within the aeolian sands of Unit 2. However, the occurrence of the stratigraphically higher Unit 3 as an inset horizon sitting lower in the landscape and outcropping on the northern bank of the creek suggests a depositional hiatus subsequent to the deposition of Unit 2. Erosion and removal of pedogenic material from Unit 2 may have taken place prior to the deposition of subsequent lacustrine sediments, but it is more likely that there was insufficient time for or conditions not conducive to pedogenesis within Unit 2 prior to the deposition of Unit 3.
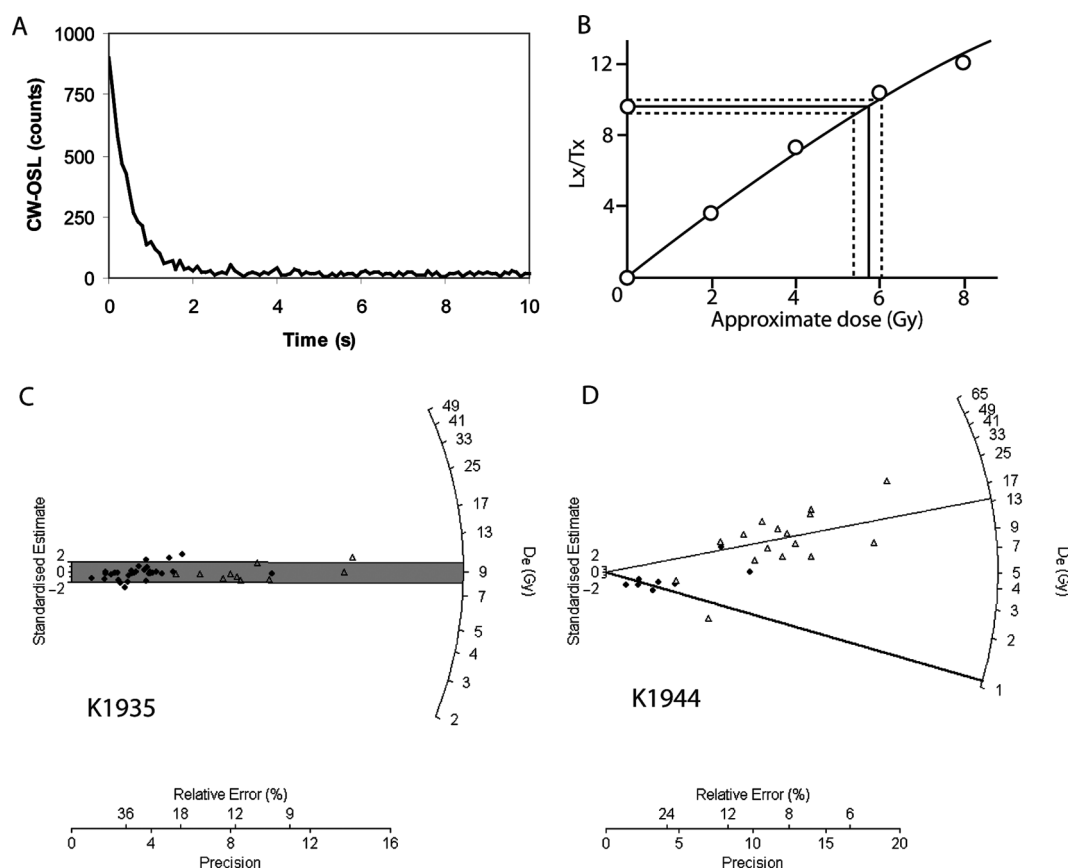
Figure 3. (A) Natural OSL decay of sample K1935 (aeolian Unit 2). (B) Indicative dose-response curve for sample K1935. (C) and (D) Radial plots showing dose distributions for both single grains (closed circles) and small aliquots (open triangles) for samples (C) K1935 and (D) K1944. The radial plots illustrate the distributions of ages for each aliquot or grain (right-hand radial y-axis) relative to precision (x-axis). For K1935, the shaded area corresponds to 2σ from the calculated D_e. For K1944, the two lines correspond to the calculated D_e for single-aliquot and SG analyses. Note that single and multiple grain data fit within a single Gaussian distribution for K1935. By contrast, single grain data for K1944 are dominated by very young signals, compared with a broader scatter of D_e values (though dominated by older signals) arising from multiple grain measurements

Unit 3 is a relatively organic-rich horizon comprising interbedded lacustrine and alluvial sediments, with the alluvial laminae increasing in frequency upwards within the unit. The lacustrine laminae vary from very fine, relatively organic-rich silty clays to sandy clays containing roots, representing relatively deeper and shallower lacustrine facies, respectively. The sedimentary sequence within Unit 3 therefore represents repeated lake transgression and regression. The finer, deeper lacustrine sediments can be associated with an estimated lake depth of 15–18 m (estimated to be deposited at ~3 m depth at this site), the root-bearing sandy clays correspond to shallow water close to the shoreface and therefore ~15 m lake depth, and the deposition of alluvial sediments indicates lake retreat to <15 m depth. Unit 3 represents the most recent occurrence of 15–18 m deep lake conditions, since it lies stratigraphically below the alluvial sands of Unit 4. The deposition of alluvial sediments indicates the initiation of the Collector Creek at this site in response to lake regression. Alluvial deposition has persisted more or less continuously to the present day, with the exception of a phase of aeolian dust deposition (Unit 5). Unit 5 is spatially discontinuous and is overlain by a thin veneer (<10 cm) of alluvial sand corresponding to Unit 4. The deposition of aeolian dust most likely indicates a dry lake basin, at least at its northern end. An analogue for this type of environment prevails at Lake George presently, with active entrainment and transport of aeolian

dust from unvegetated scalds on the dry lake surface downwind to the CC site, 18 m embankment, and the ridge which forms the eastern margin of the lake basin.

Vault Embankment site. The stratigraphy at the VE site appears to comprise four main units and is overlain by reworked material and spoil excavated from a small quarry immediately to the east. Three and two units, respectively, are exposed at the two sample points which lie approximately 10 m apart (Figure 4B). The most distinctive unit (2) comprises beach gravels with a substantial component of clay and silt, which most likely represents illuviation of fine-grained material down the stratigraphic sequence. Unit 2 was observed at both sample points, and is underlain at the southern point by clay-rich sands (Unit 1) representing a relatively lower-energy shoreline preceding the Unit 2 beach gravels. At both sample points, the sequence appears to fine upwards from Unit 2, indicating progressively lower-energy shoreline conditions. However, there are some sedimentological differences between these upper units at the two sample points, which suggest that they may represent two distinct depositional phases. Unit 3, exposed at the southern sample point, is a clay-rich sand similar to Unit 1. Unit 4 is a relatively finer-grained shoreline mud (silt and clay) horizon exposed at the northern sample point. It is possible that these

units represent the same sequence of upward fining from Unit 2 and that subtle topographic differences between the two sample points resulted in more of the relatively finer sediments deposited slightly further north. However, it is also possible that these are two distinct units, and that an unconformity exists between them and Unit 2, obscured by quarrying.

OSL chronology

The age estimates and data used for age calculation are presented in Table 2. Seventeen OSL ages range from 14.1 ± 0.9 ka to 0.13 ± 0.02 ka (Table 2; Figure 4) and therefore span the Holocene period almost to the present day, with one anomalous age estimate of 37.3 ± 2.5 ka (K1936). The older sample (K1936) showed evidence of incomplete bleaching in contrast to the other samples. In particular, the samples both immediately higher and lower (K1942 and K1943) in the stratigraphy yielded Gaussian dose distributions and are close together in age, suggesting that these samples are more likely to be accurate. Sample K1936 has therefore been disregarded from the chronologic interpretation. Although the two samples from the VE site also show evidence of incomplete bleaching, the dose distributions of those samples are more strongly skewed towards a younger age peak, suggesting that the leading edges of those distributions are more likely to be appropriate (and accurate) compared with that for K1936.

Single grain ages for samples K1935, K1939 and K1944 are given in italics in Table 2 and used in preference to the single aliquot ages in the interpretation of the chronology. The ages calculated from single grain data lie within 2σ error of those calculated using multiple grain aliquots for the two samples from Unit 2 (K1935, K1939; see also Figure 3C). These results improve confidence in the use of small aliquots for D_e determination and support the argument that small aliquot measurements are comparable with single grain, since the signal arising from small aliquots is most likely derived from only one or two grains (Duller, 2008). By contrast, the dose distributions for single aliquot and single grain measurements of sample K1944 are not equivalent. An explanation for this may be found in the age of the sample and the number of grains yielding sufficient OSL signal. The yield of sufficiently luminescent grains of those measured which produced a satisfactory dose-response curve in response to the SAR protocol, and met criteria for recycling ($\pm 20\%$), was between 1 and 5%. Sample K1944 produced the lowest yield of useful grains (1.3%), dominated by very young grains but with two substantially older data points (Figure 3D). The low yield of useful grains was most likely due to the very low dose received by the sample, resulting in a small luminescence signal which for many grains was indistinguishable from background. The older outliers emit a brighter signal which would dominate a small aliquot comprising mostly very young grains. For this reason the single grain approach is considered more reliable in preference to single aliquots in the case of very young material.

The OSL ages from the Collector Creek section all occur within stratigraphic order, with the exception of samples from Unit 2 (Table 2; Figure 4). The five accepted samples dated from aeolian Unit 2 lie within 2σ error of one another, suggesting geologically instantaneous deposition of this unit. The sample collected from lacustrine Unit 1 is also effectively the same age as overlying Unit 2.

OSL characteristics

The OSL behaviour of the samples from the Collector Creek site indicates that these sediments are generally well suited to OSL dating using the SAR protocol. Most samples exhibit intense initial OSL signals with rapid decay indicative of dominance by the fast component (Figure 3A). Linearly modulated OSL signal measurement of sample K1935 confirms this observation (Fitzsimmons *et al.*, 2010). The brightest OSL signals occur in samples from Unit 2. IRSL signals and thermal transfer for all samples are low. Aliquots yield dose response characteristics corresponding to an exponential function (Figure 3B), as can be expected for samples with D_e values of <15 Gy. All samples yield data with recycling values within 10% and 20% of unity for single aliquot and single grain measurements, respectively.

The sensitivity of samples based on both the natural OSL signals were calculated from both single aliquot and single grain data. These data are given in Table 3, expressed as the mean and standard deviation of all aliquots or grains. Luminescence sensitivity relative to depositional context and age, both for single aliquots and single grains, is shown in Figure 5. Figure 5 demonstrates that sensitivity between aliquots and grains is highly variable, but that this range of variability is reproduced across samples regardless of depositional context or age.

Discussion

OSL characteristics as a diagnostic tool for sediments

Recent investigations into the luminescence sensitivity of Australian quartz suggest that sediments become increasingly sensitive (that is, emit more luminescence per unit absorbed radiation dose) in response to repeated cycles of reworking and burial (Fitzsimmons *et al.*, 2010), or laboratory-equivalent cycles of stimulation by light and irradiation (Pietsch *et al.*, 2008). The implication of this is that sediments may be able to be characterised by sediment source and history on the basis of their luminescence sensitivity. Earlier work on thermoluminescence (TL) signal characteristics from down a core profile taken at Lake George (Mortlock and Price, 1984) also suggests that sediment input by different sources through time may influence the luminescence signal at a given site. In addition, Fitzsimmons *et al.* (2010) found evidence suggesting that depositional context influences quartz brightness, with aeolian sediments from Lake George exhibiting sensitivity one order of magnitude greater than shoreface- and lacustrine-deposited quartz grains. It was suggested that the nature of exposure to sunlight, which resets the luminescence signal immediately prior to deposition, also plays a role in the sensitisation of quartz (e.g. Li and Wintle, 1992).

This study, in which samples were collected from the same site but from a variety of depositional contexts, provides an opportunity to investigate further the findings of Fitzsimmons *et al.* (2010) that depositional context influences quartz luminescence sensitivity. The sensitivity distributions of Lake George single aliquot and single grain samples, relative to depositional context and age, are shown in Figure 5. Of primary interest here is the natural sensitivity to samples, which represents the inherited characteristics of sediments within the natural system. Natural sensitivity for small aliquots is highly variable but does not appear to be dependent on depositional context (Figure 5A) or age (Figure 5B). This lack of correlation contradicts the preliminary findings of Fitzsimmons

Table 2. Equivalent dose (D_e), dose rate data and OSL age estimates for all samples

Sample ID	D_e (Gy)	Moisture content (%)	Depth (m)	Radionuclide concentrations			External γ dose rate (Gy/ka)[f]	Cosmic ray dose rate (Gy/ka)[g]	Total dose rate (Gy/ka)	Strat. Unit	Age estimate (ka)
				K (%)[d]	Th (ppm)[e]	U (ppm)[e]					
Collector Creek section											
K1944	13.6 ± 0.3[a]	3 ± 3	0.12	0.45 ± 0.02	4.94 ± 0.25	1.01 ± 0.05	0.40 ± 0.10	0.23 ± 0.04	1.19 ± 0.11	5	11.5 ± 1.2
	1.3 ± 0.2[b]										1.1 ± 0.2
K1937	0.19 ± 0.02[a]	7 ± 3	0.16	0.73 ± 0.04	7.96 ± 0.40	1.50 ± 0.08	0.38 ± 0.01	0.23 ± 0.03	1.44 ± 0.07	4	0.13 ± 0.02
K1938	2.2 ± 0.2[a]	6 ± 3	0.32	0.39 ± 0.02	4.04 ± 0.20	0.77 ± 0.04	0.39 ± 0.01	0.23 ± 0.02	1.06 ± 0.04	4	2.0 ± 0.2
K1966	0.85 ± 0.10[a]	7 ± 3	0.28	0.55 ± 0.03	5.71 ± 0.29	1.14 ± 0.06	0.51 ± 0.02	0.23 ± 0.02	1.36 ± 0.05	3	0.62 ± 0.08
K1967	0.53 ± 0.14[a]	9 ± 3	0.47	0.54 ± 0.03	6.15 ± 0.31	1.22 ± 0.06	0.47 ± 0.02	0.22 ± 0.02	1.31 ± 0.05	3	0.40 ± 0.11
K1968	0.30 ± 0.02[a]	5 ± 3	0.64	0.20 ± 0.01	1.61 ± 0.08	0.37 ± 0.02	0.45 ± 0.02	0.22 ± 0.02	0.89 ± 0.03	3	0.34 ± 0.03
K1969	3.2 ± 0.3[a]	9 ± 3	1.1	0.47 ± 0.02	6.31 ± 0.32	1.08 ± 0.05	0.59 ± 0.02	0.20 ± 0.02	1.36 ± 0.04	3	2.4 ± 0.2
K1970	7.3 ± 0.4[a]	12 ± 3	1.84	0.53 ± 0.03	7.14 ± 0.36	1.42 ± 0.07	0.41 ± 0.02	0.19 ± 0.01	1.22 ± 0.05	3	6.0 ± 0.4
K1935	8.9 ± 0.3[a]	7 ± 3	0.45	0.31 ± 0.02	2.78 ± 0.14	0.60 ± 0.03	0.33 ± 0.01	0.22 ± 0.02	0.89 ± 0.03	2	10.0 ± 0.5
	8.9 ± 0.3[b]										10.0 ± 0.5
K1939	6.2 ± 0.2[a]	9 ± 3	0.5	0.29 ± 0.01	2.27 ± 0.11	0.46 ± 0.02	0.31 ± 0.01	0.22 ± 0.02	0.82 ± 0.03	2	7.6 ± 0.4
	7.4 ± 0.6[b]										9.0 ± 0.8
K1940	7.1 ± 0.3[a]	10 ± 3	0.55	0.31 ± 0.02	2.13 ± 0.11	0.45 ± 0.02	0.31 ± 0.01	0.22 ± 0.02	0.82 ± 0.03	2	8.6 ± 0.5
K1941	8.1 ± 0.7[a]	12 ± 3	0.62	0.30 ± 0.02	2.31 ± 0.12	0.46 ± 0.02	0.34 ± 0.01	0.22 ± 0.02	0.84 ± 0.03	2	9.7 ± 0.8
K1942	7.4 ± 0.2[a]	13 ± 3	0.68	0.31 ± 0.02	2.80 ± 0.14	0.47 ± 0.02	0.34 ± 0.01	0.22 ± 0.02	0.86 ± 0.03	2	8.6 ± 0.4
K1936	36.4 ± 2.0[a,c]	7 ± 3	0.73	0.41 ± 0.02	2.80 ± 0.14	0.57 ± 0.03	0.36 ± 0.01	0.22 ± 0.02	0.98 ± 0.04	2	37.3 ± 2.5
K1943	9.3 ± 0.3[a]	16 ± 3	0.95	0.44 ± 0.02	5.21 ± 0.26	0.86 ± 0.04	0.46 ± 0.02	0.21 ± 0.02	1.12 ± 0.04	1	8.3 ± 0.4
Vault Embankment											
K2030	4.6 ± 1.3[a,c]	3 ± 2	0.16	0.46 ± 0.02	5.62 ± 0.28	0.87 ± 0.04	–[h]	0.23 ± 0.06	1.24 ± 0.08	4	3.7 ± 1.0
K2031	13.3 ± 0.5[a,c]	3 ± 2	0.58	0.38 ± 0.02	3.31 ± 0.17	0.64 ± 0.03	–[h]	0.21 ± 0.02	0.94 ± 0.04	3	14.1 ± 0.9

[a] Multiple grain aliquots comprising <100 grains.
[b] Single grain measurements. All other parameters for age calculation remain the same as for multiple grain analysis.
[c] Calculated as minimum age. All other D_e values calculated using the central age model of Galbraith et al. (1999).
[d] Measured by ICP-OES (Genalysis Laboratories, Perth, Australia).
[e] Measured by ICP-MS (Genalysis Laboratories, Perth, Australia).
[f] Derived from *in situ* portable sodium iodide gamma spectrometry.
[g] Cosmic ray dose-rates were calculated following Prescott and Hutton (1994) according to current depth from surface, based upon values for sediment density, altitude, latitude and longitude.
[h] Gamma spectrometry not undertaken for this sample. Beta and gamma dose rate components calculated by converting radioactive element concentrations using conversion factors of Adamiec and Aitken (1998).
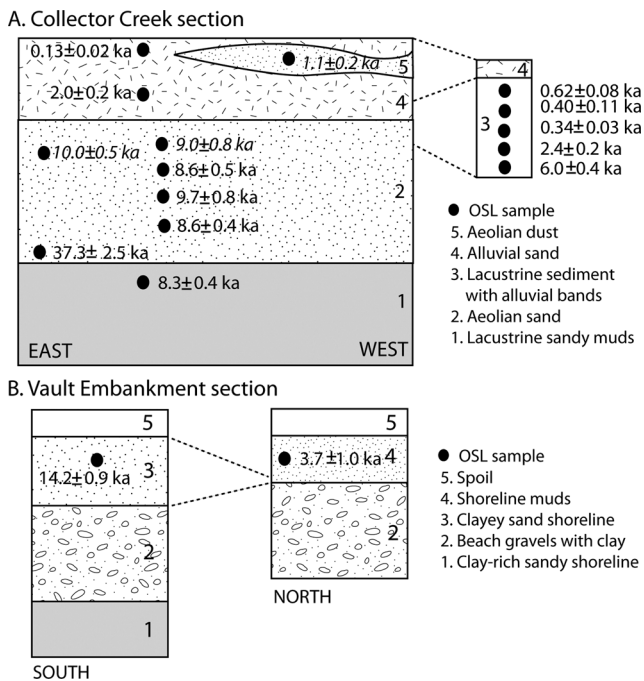
A. Collector Creek section

Figure 4. Stratigraphy and chronology of (A) Collector Creek site, (B) Vault Embankment site

et al. (2010) which showed that aeolian sediments are substantially brighter than quartz deposited by other means. It does not, however, preclude an association between natural sensitivity and sediment history or source. All of the quartz sampled at this site comprises a mixture of material derived from reworked shorelines,

catchment streams, alluvial fans and colluvium sourced directly from bedrock on the basin margins, all of which may have been transported around the lake during high lake phases. The natural sensitivity of small aliquots, being derived from the combined signal of multiple grains reflecting the mixture of sources, will therefore exhibit variability consistent with such a mixture. The variability in natural sensitivity for single grains from sample K1944 (Figure 5C) supports this hypothesis. The natural sensitivity hypothesis might better be investigated using single grain analysis from a site such as the one studied by Mortlock and Price (1984). Their study investigated thermoluminescence signal variation down a core from the northwestern part of the lake floor adjacent to alluvial fans from the western horst escarpment. Sediment input through time was alternately dominated by lacustrine and alluvial fan material at their site, and was interpreted to influence the thermoluminescence signal down the core. Such a site would enable a more clear-cut elucidation of natural OSL signal variations due to sediment input and depositional context through time.

Holocene hydrologic variability at Lake George

This study provides a chronologic framework for Holocene hydrological variability at Lake George, based on 17 OSL ages taken from two critical lake margin sites. The high-frequency sampling of the stratigraphy at these sites, coupled with direct dating of the timing of sediment deposition using OSL techniques, ensures the most robust chronology available for Holocene lake-level change at Lake George.

The chronology from the two sites at the northern end of Lake George indicates a trend towards lake regression to its present

Table 3. Summary of sediment types and luminescence sensitivity characteristics. Single grain data are distinguished by italics

| Laboratory code	Sediment description	D_e (Gy)	Natural sensitivity $\pm \sigma$ (cts/s/Gy)
K1935	Aeolian sand	8.9 ± 0.3	2460 ± 4240
		8.9 ± 0.3	*48 ± 62*
K1936	Aeolian sand	36.4 ± 2.0	285 ± 203
K1937	Alluvial sand	0.19 ± 0.02	5126 ± 9682
K1938	Alluvial sand	2.2 ± 0.2	1550 ± 1395
K1939	Aeolian sand	6.2 ± 0.2	1699 ± 661
		9.6 ± 0.5	*60 ± 49*
K1940	Aeolian sand	7.1 ± 0.3	1209 ± 522
K1941	Aeolian sand	8.1 ± 0.7	1505 ± 1133
K1942	Aeolian sand	7.4 ± 0.2	957 ± 427
K1943	Lacustrine sandy muds	9.3 ± 0.3	934 ± 573
K1944	Aeolian fine sand (dust)	13.6 ± 0.3	3066 ± 3808
		1.3 ± 0.2	*137 ± 103*
K1966	Lacustrine clayey sands	0.85 ± 0.10	2259 ± 2860
K1967	Lacustrine clayey sands	0.53 ± 0.14	1649 ± 936
K1968	Lacustrine clayey sands	0.30 ± 0.02	1831 ± 1041
K1969	Lacustrine sandy clays	3.2 ± 0.3	2403 ± 837
K1970	Lacustrine gravelly sandy clays	7.3 ± 0.4	4232 ± 5974
K2030	Lake margin fine mud and dust	4.6 ± 1.3	163 ± 172
K2031	Shoreface dust-rich sand	13.3 ± 0.5	56 ± 40
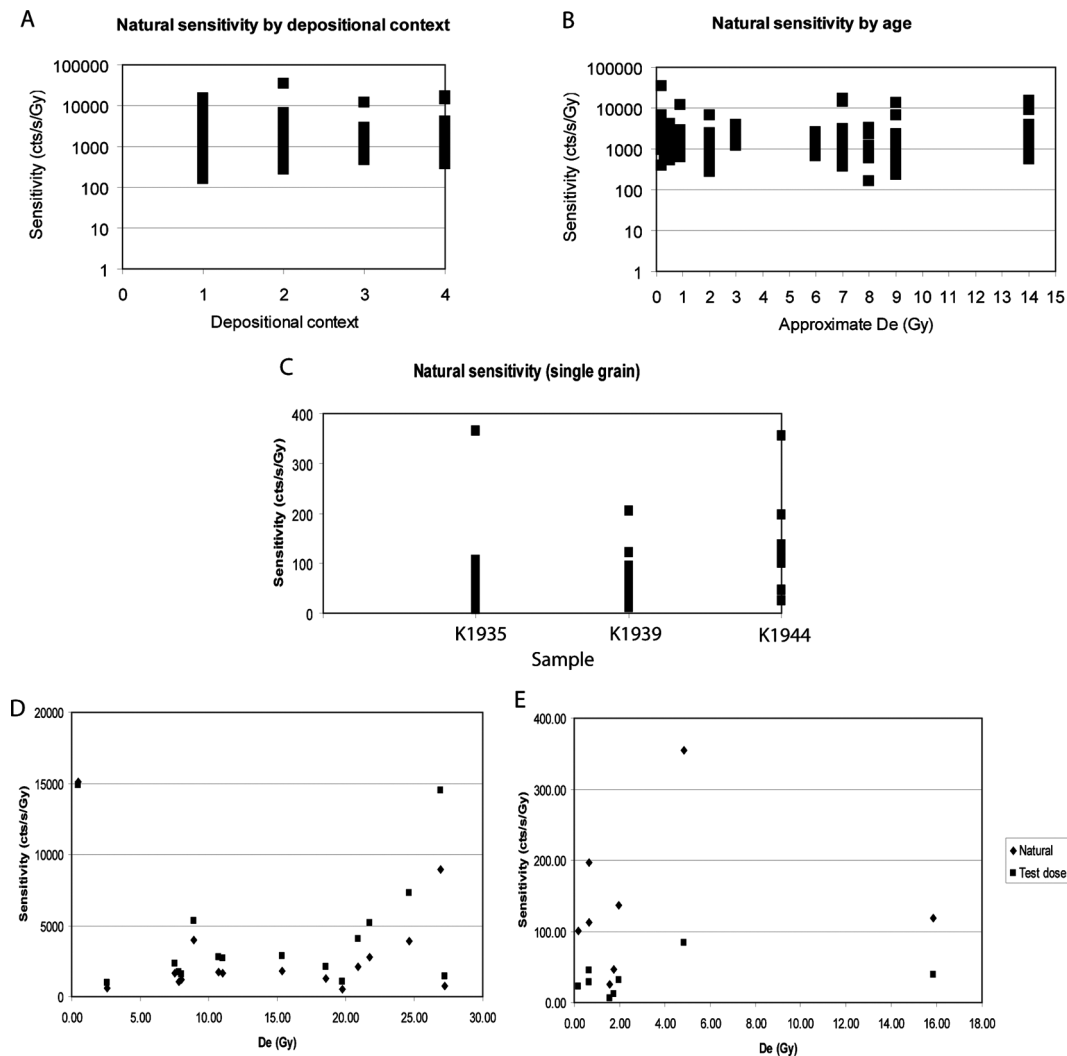
Figure 5. Plots showing the relationship between luminescence sensitivity, age and depositional context. (A) Natural luminescence sensitivity versus depositional context calculated using small aliquot data, where 1 is aeolian, 2 is alluvial, 3 is lacustrine sandy muds (Unit 1), 4 is lake transgressive/regressive sequence (Unit 3). (B) Natural luminescence sensitivity versus age (D_e in Gy) for small aliquots. Note the logarithmic scale for sensitivity in graphs (A) and (B). (C) Natural luminescence sensitivity by sample for single grain data (aeolian sediments). (D) Natural luminescence sensitivity versus age (D_e in Gy) for small aliquots of aeolian sample K1944 (Unit 5). (E) Natural luminescence sensitivity versus age (D_e in Gy) for single grains of sample K1944

ephemeral state over the Holocene period, with three major periods of 15–18 m high lake level stands and three confirmed phases of much shallower lake levels (including the present ephemeral lake phase, see Figure 6). The Holocene was preceded by 11.5 m deep permanent lake conditions, as evidenced by the 14.2 ± 0.9 ka age estimate from the shoreline deposit at the VE site. Substantially deeper permanent freshwater lake conditions, with the lake possibly extending up to the 18 m embankment just to the east of the CC site, prevailed around approximately 8.3 ka with the deposition of lacustrine Unit 1. There is no clear evidence of a ~8 ka high lake phase and the two subsequent high lake phases at the VE site, however the stratigraphy may have been removed by ploughing and quarrying (Section OSL Chronology). The development of a palaeosol on Unit 1 suggests a depositional hiatus, however the OSL ages for Units 1 and 2 are effectively the same. Since there is no evidence for bioturbation either within the sediments or the OSL dose distributions for any of these samples, we must infer that the depositional hiatus between Units 1 and 2 was brief although sufficient for pedogenesis to take place, and that the lake reached ~18 m and regressed

slightly to the CC site between ~10 and 8 ka. Despite the limitations of previously published chronologies, this event correlates with permanent freshwater conditions around 12.2–8.5 kcal. yr BP interpreted from ostracods taken from a core in the northern part of the lake (De Deckker, 1982), and the prevalence of isolated patches of tall open eucalypt forest within the basin, indicating relatively wetter conditions, based on pollen reconstructions (Singh *et al.*, 1981a; Singh and Geissler, 1985). Significantly, however, the ~10–8 ka age of Unit 2, which matches Coventry and Walker's (1977) description of the Prairie Sands, is substantially older than their radiocarbon dates of ~4.7 kcal. yr BP and ~1.8 kcal. yr BP for that unit. Although those samples were taken from further east in the lake basin and therefore may correspond to a later-deposited aeolian unit, the discrepancy between the chronologies may alternatively reflect contamination by younger organic material for the radiocarbon dating (compared with consistent OSL behaviour for the aeolian quartz sampled in this study).

The incision of the land surface and subsequent deposition of the alternating lacustrine and fluvial sediments of Unit 3, at 15–18 m
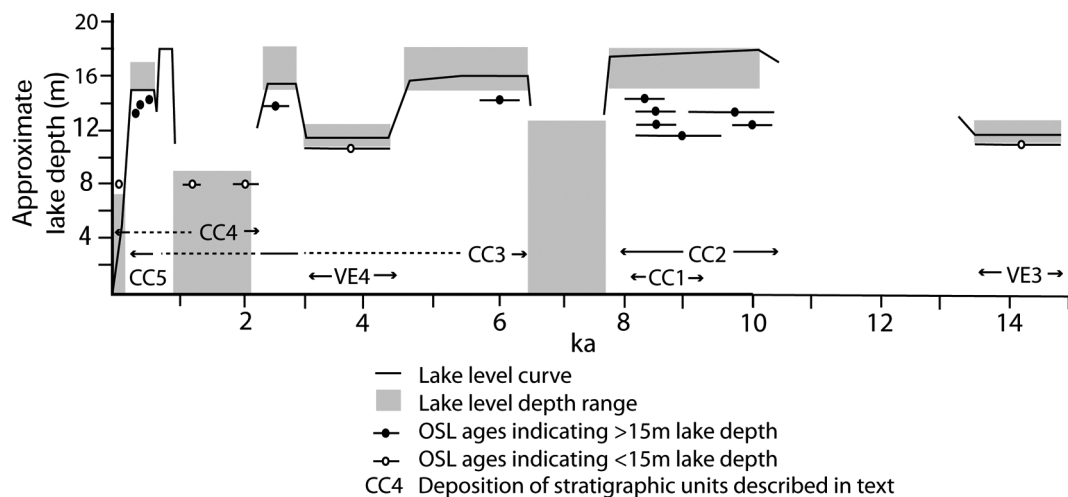
Figure 6. Holocene hydrological variability at Lake George

elevation above lake depocentre, suggests that the lake did not occupy this depth until approximately 6 ka. This is the oldest age for Unit 3. Several laminae within Unit 3 suggest relatively deep permanent water conditions, however the lack of lacustrine sediments overlying Unit 2 indicates that the lake did not reach a level above the level of Unit 3. Coventry (1976) inferred a lake transgression to 25 m depth around this period (8–7 kyr BP) based on bracketing radiocarbon dates from shorelines, however since there is no preservation of such deep lake conditions on the southern bank of the study site, it is more likely that the lake reached 18 m depth and no deeper. Unit 3 represents fluctuating, perhaps ephemeral lake levels responding to seasonal or longer-term dry conditions, increasingly dominated by alluvial deposition during lake regression, extending from ~6 to 0.3 ka. This is consistent with the deposition of shoreline muds at 3.7 ± 1.0 ka indicating 11.5 m lake depth at the VE site, which places a constraint on lake levels at that time. A short-lived phase of aeolian dust deposition, indicating dry lake conditions, took place at approximately 1.1 ka with the deposition of Unit 5. The most recent lake highstand to 15–18 m depth persisted ~0.6–0.3 ka, based on three samples within 2σ error of one another. Unit 3 intercalates with the fluvial sediments of Unit 4, which were deposited from ~2 ka to the present day. This sequence indicates lake regression to substantially less than 15–18 m depth over the last 2 kyr with the exception of the ~0.6–0.3 ka lake transgression, and is reflected in the increasing dominance of alluvial deposition on the lake floor. This interpretation of the chronology is in agreement with that of De Deckker (1982), who inferred ephemeral lake conditions with several lake transgressions over the period 8.5–3.2 kcal. yr BP, and often dry but ephemeral lake conditions over the most recent 3 kcal. yr BP. Pollen evidence suggests that low open sclerophyll forests dominated the landscape throughout this period (Singh *et al.*, 1981a; Singh and Geissler, 1985), suggesting a comparatively dry climatic regime. Furthermore, Coventry and Walker (1977) report increasing frequency of alluvial fan activity on the lake margins overlying lacustrine and lake margin sediments, suggestive of relatively drier conditions and lake regression.

Southeastern Australian context

The chronology at the CC site indicates the occurrence of three major periods of 15–18 m high lake-level stands at approximately

10–8, 6–2.4 and 0.7–0.3 ka. The two later high lake-level stands represent longer-lived phases which saw lake levels fluctuate between 11.5 and 15+ m depth, with a trend towards increasing frequency of alluvial activity on the basin floor as the lake regressed. Three confirmed phases of much lower (<15 m, possibly substantially lower) lake levels have been constrained to approximately 8–6 ka (aeolian deposition), ~3.7 ka (11.5 m depth at the VE site), 2.4–0.9 ka (including aeolian deposition) and the most recent 200–300 years (based on historical records).

This variability in lake palaeohydrology over the Holocene period reflects climatic conditions (as precipitation versus evaporation) over the Lake George catchment in the southeastern Australian highlands region, and contributes to an emerging picture of climatic variability over the last 10 kyr. In particular, the timing of high lake levels at Lake George between ~10 and 2.5 ka correlates with the identification of a gap in the alluvial record in southeastern Australian catchments between ~10 and 4.5 ka (Cohen and Nanson, 2007), raising an hypothesis of relatively wet conditions throughout the early to mid Holocene. In addition, high lake levels between 10 and 8 ka at Lake George correspond to high lake levels in closed lake basins further afield in western Victoria (approximately 500 km to the southwest) between 9 and 7.5 ka (Jones *et al.*, 1998), as well as increased discharge from the neighbouring Murray-Darling catchment around 9.5–7.5 ka (Gingele *et al.*, 2007). Early-Holocene palaeoecological records suggest increased forest cover across the semi-arid (Cupper, 2005) to temperate sub-humid regions of southeastern Australia (Hope *et al.*, 2004). The combination of these environmental responses substantiates the hypothesis for increased precipitation across southeastern Australia, including Lake George, through the early Holocene. Although not directly dated in this study because of a depositional hiatus at the sample sites, the inferred lower lake levels between 8 and 6 ka indicate a relatively drier climate, which is echoed in falling lake levels at Lake Keilambete in western Victoria (Bowler, 1981) and decreased fluvial output at the Murray River mouth (Gingele *et al.*, 2007) around 7.5–5 ka. However, several studies from closed lakes (Jones *et al.*, 1998) and swamps (Sweller and Martin, 2001; Hope *et al.*, 2004) suggest wetter conditions across southeastern Australia from 7.5 to 7 ka. Significantly, however, these studies and others from a transect across the arid to sub-humid zone,

based on a variety of records including pollen (Singh and Luly, 1991; Cupper, 2005), rejuvenation of upland swamps, lake levels and fluvial discharge rates (Cohen and Nanson, 2007) suggest that the mid-Holocene wetter climates prevailed until around 3 ka. This phase was shorter-lived but nevertheless prevalent in the arid and semi-arid centre of the continent (Singh and Luly, 1991; Cupper, 2005).

The sedimentological evidence for lower lake levels at the CC site over the last 2.5 ka suggests a trend towards drier climatic conditions, despite short-lived pulses of lake transgression such as the one from Unit 3 and dated to approximately 0.7–0.3 ka. This relatively drier, more variable climate can also be seen in other environmental records from southeastern Australia. Increased river aggradation corresponding to drier, less stable regional climates from 3.3 to 0.9 ka was identified in the Naas catchment approximately 100 km southwest of Lake George (Eriksson *et al*., 2006). The alluvial record is supported by an assessment of catchment studies in the southeastern Australian region that point towards increasing alluvial sedimentation through aggradation over the most recent ~4 kyr (Cohen and Nanson, 2007), and interpreted to be a response to drier, less stable climates influenced by episodic threshold-driven fluvial processes in the upper catchments. Pollen records from swamps in the semi-arid (Cupper, 2005) and sub-humid zones (Hope *et al*., 2004) suggest reduced vegetation cover indicative of drier climates between 4 and 0 ka. Increased incidence of shrublands in the semi-arid zone was also interpreted to be coincident with desert dune reactivation (Cupper, 2005), an observation consistent with increasing dune activity in the arid zone (Fitzsimmons *et al*., 2007) and increasing incidence of dust over southeastern Australia (Gingele *et al*., 2007) over the last 4 kyr. Models of lake levels from western Victoria also suggest lake regression from ~3 ka (Jones *et al*., 1998). A recent synthesis of records from eastern Australia concluded that late-Holocene climates were generally drier and more variable, attributable to the increasing influence of El Niño-Southern Oscillation (ENSO) conditions (Donders *et al*., 2007).

Conclusions

The OSL dating chronology at Lake George indicates three distinct periods of 15–18 m high lake-level stands at approximately 10–8, 6–2.4 and 0.7–0.3 ka. There is a trend towards increasing frequency of alluvial activity on the basin floor as the lake regressed over the last 6 kyr. Three confirmed phases of lower (<15 m) lake levels have been constrained to approximately 8–6, ~3.7 (11.5 m depth), 2.4–0.9 and the most recent 0.3–0 ka. It is difficult to directly correlate the chronology from this study with that of earlier work at Lake George owing to the potential unreliability of radiocarbon dating within an inherently open system. However, the timing of hydrologic variability at Lake George is broadly synchronous with wetting and drying of the southeastern part of the Australian continent throughout the Holocene.

The luminescence characteristics of the quartz from Lake George indicate suitability for dating using OSL. However, use of natural luminescence sensitivity as a diagnostic tool for sediment depositional context or age appears not to be appropriate in this context. Further work is required to elucidate potential patterns in inherited quartz sensitivity by studying single grains from sites where variations in depositional context or sediment source are more clearly defined.

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