**SUPPLEMENTARY MATERIAL**

**LUMINESCENCE DATING**

Aeolian landforms in Tasmania, and in Australia in general, have been dated mainly by luminescence methods. Indeed, the advent of luminescence dating has revolutionised the understanding of aeolian environments (e.g., Singhvi and Porat, 2008; Duller, 2016) and of late Quaternary history in general (Roberts and Lian, 2015).

Luminescence dating is based on the premise that natural minerals contain impurities and structural defects that can act as traps for free electrons. At ambient temperatures some of these traps can hold electrons for only a few hours or less, but there are others that can hold them for millions of years or more, and these are referred to as thermally stable or deep traps. All traps can be emptied by exposure to sufficient heat (~400°C), but only some traps can be emptied by exposure to light. Free electrons are produced when minerals absorbs ambient radiation. If a sediment sample is buried in a sedimentary landform, for example, electron traps in the mineral grains will fill at a rate proportional to the production of free electrons, the environmental dose rate. If the sediment sample is uncovered and exposed to a few seconds of direct sunlight, light-sensitive electron traps will be emptied. If the sample is exposed to sufficient heat, both light-sensitive and light-insensitive traps will be emptied. In the laboratory, experiments are designed that allow for an estimate to be made of the dose of laboratory radiation that will produce the same intensity of luminescence as the dose absorbed by the sample in the environment since burial; this is referred to as the equivalent dose. A sample’s luminescence age is simply its equivalent dose divided by its environmental dose rate. The various luminescence dating methods that have been developed since the 1960s mainly involve variations in the technique used to estimate equivalent dose, and in the methods by which the most light-sensitive thermally stable traps are selected. The evolution of luminescence dating techniques, and their design and applicability has been reviewed in detail by Lian and Roberts (2006) and Wintle (2008) and in these reviews illustrative examples are also given; a concise account is given below, with an emphasis on quartz as it has been the preferred chronometer for dating aeolian landforms in Australia.

***Thermoluminescence dating***

Luminescence dating has its roots in thermoluminescence (TL) dating of fired material such as pottery (Aitken et al. (1964, 1968); and see review by Roberts (1997)). The first detailed accounts of reliable methods for TL dating sunlight-exposed sediments were reported by Wintle and Huntley (1979a, b, 1980, 1982). The most widely used TL dating methods are relatively similar in that to estimate equivalent dose they rely on the measurement of many multi-grain aliquots of prepared sediment. The simplest methods involve leaving some of the aliquots as is (the ‘naturals’, N), while the remainder are given various increasing doses of laboratory radiation producing an N+dose set of aliquots. All of the aliquots are heated one at a time in an inert atmosphere from room temperature to about 600°C while the TL is recorded; each aliquot produces a plot of TL intensity as a function of temperature, which is often called a glow curve. Glow curves consist of several overlapping peaks that represent trap populations with various sensitivities to light and different thermal stabilities; the peaks that appear at higher temperatures are those that are thermally stable over time periods of interest.

In the simplest case an equivalent dose value is estimated by plotting the TL measured at a particular temperature as a function of laboratory dose, which produces a dose-response curve (or ‘growth curve’). The TL recorded from the natural aliquot(s) is interpolated onto the dose-response curve to find the equivalent dose (Wintle and Huntley, 1982, fig. 1b). If the heating causes sensitivity change in the mineral being analysed, then a different approach is needed. This involves plotting the N and N+dose aliquots together, fitting a curve to all the data, and extrapolating it to where it intersects the dose axis (Wintle and Huntley 1982, fig. 1c). An expansion of this method accounts for the presence of a residual TL signal (from incomplete, or partial bleaching prior to burial). This method involves exposing some of the natural and dosed aliquots to a short duration of light to empty the most light-sensitive traps, producing a separate N+dose+bleach set of aliquots. The growth curves from both sets of aliquots are plotted on the same graph and extrapolated to where they intersect above the dose axis, and the equivalent dose is read at that point. This is the ‘partial bleach’ technique (Wintle and Huntley, 1982, fig. 9). In some cases the partial bleach technique is simplified by replacing the N+dose+bleach set of aliquots by a single N+bleach point and a line is extended from it to where it intersects the N+dose curve. In other cases, where it is suspected that the sample received extended sunlight exposure prior to burial, the N+dose+bleach set (or N+bleach aliquot) is given a longer sunlight bleach to empty all light-sensitive traps, and this is referred to as the ‘total bleach’ method (Wintle and Huntley, 1979 a; Singhvi et al., 1982). Another approach is to give a set of aliquots prolonged exposure to light, to entirely remove the light-sensitive TL signal, and then give them various doses to construct an N+bleach+dose (regenerative) set. This regenerative set of data is shifted onto the N+dose set, and the magnitude of the shift is taken as the equivalent dose value; this technique is referred to as the ‘Australian Slide’ (AS) method due to its initial application to date a sequence of ancient coastal dunes in South Australia (Prescott et al. 1993). This method is preferred when the extrapolation of dose response curves required for the partial bleach method is large, which is common for old samples. The Australian Slide method also has the advantage of detecting the presence of any sensitivity change in the mineral (incurred by dosing, bleaching, and heating the sample in the laboratory) by comparing quantitatively the shapes of the two growth curves.

For TL dating techniques, growth curves are constructed at various read temperatures, and these produce a set of equivalent dose values that are plotted as a function of temperature. For a sample that has received sufficient sunlight exposure prior to burial, and for which growth curve data are fitted with the appropriate function (curve), the equivalent dose values should plot as a plateau, and, for quartz, if this is the case, values between 325 and 400 °C (e.g., Huntley and Prescott, 2001) are typically averaged and used together with the sample’s environmental dose rate to estimate a TL age.

***Optically stimulated luminescence dating***

A new luminescence dating technique was developed by Huntley et al. (1985) in which luminescence is produced by stimulation with light of a specific wavelength, or wavelength range, instead of by heat. This technique is called optical dating, and it is also commonly referred to as optically-stimulated luminescence (OSL) dating. It has advantages over TL dating in that the most light-sensitive electron traps can be measured directly (the OSL signal bleaches much more rapidly than the TL signal), and the experimental setup is simpler which leads to better precision. The first OSL dating techniques were developed directly from those used for TL dating and therefore also required that many aliquots be made to construct dose response curves. Because aliquots cannot be made to be identical, they are normalised using the OSL measured over a short duration before any doses of laboratory radiation are administered. Since laboratory irradiation populates both thermally stable and thermally unstable traps, the aliquots are heated together before the OSL is measured to empty electrons from thermally unstable traps which would not have remained filled in the environment over geological timescales. This ‘preheating’ sometimes causes the unwanted transfer of electrons from light-insensitive traps to the traps of interest for dating, but it can be accounted for by including an N+dose+bleach set of aliquots (Huntley et al., 1993). Aliquots are measured one at a time and the OSL is recorded as a function of time, typically for 50 or 100 s. The result is a luminescence decay curve (shine-down curve) for each aliquot which is the sum of several individual curves (signal components), each representing a specific trap or trap population. For quartz, some of these signal components are useful for dating, while others are not; not all quartz samples have the same signal components, and the prominence of these components vary from sample to sample, and even between aliquots or single grains of the same sample. Dose response curves are constructed over intervals of measurement time and this approach can be used to crudely select the signal components of interest (there are more complex methods that can be used to more thoroughly and objectively separate signal components). Equivalent dose is found by extrapolation of the N+dose and N+dose+bleach data to where they intersect above the dose axis. In some cases the N+dose+bleach curve is omitted, if thermal transfer is found to be negligible, or it is replaced by a single N+bleach point as is done in the total bleach method used in TL dating. The AS method, already described for TL dating, is also applicable to OSL dating.

*The single-aliquot regenerative-dose (SAR) technique*

Shortly after the development of the first multiple aliquot OSL dating methods, protocols were introduced that allowed an equivalent dose value to be determined from a single aliquot of prepared sediment, which could consist many grains or just a single grain (Stokes, 1994; Murray and Roberts, 1997). This allows for much small sample sizes to be measured, and samples that consist of populations of grains with various environmental bleaching histories, or different luminescence signal characteristics, can potentially be scrutinised; it also eliminates the need for normalisation. This lead to the development of statistical techniques that can be used to estimate representative equivalent dose values (and ages) from those produced from many aliquots (e.g., Galbraith et al., 1999; Roberts et al., 2000).

The first single aliquot techniques consisted of a simple single-aliquot additive-dose (SAAD) protocol, and a ‘single-aliquot regeneration and added-dose’ (SARA) protocol (Mejdahl and Bøtter-Jensen, 1994). But because these protocols required that each aliquot be dosed, heated, and measured several times, the sensitivity of the aliquot changed with each cycle (e.g., Armitage et al., 2000) and this had to be corrected for. This correction was usually done by monitoring sensitivity changes in a second aliquot of the same sample. These methods were therefore not strictly single-aliquot protocols, but they later became so by instead monitoring changes to the sensitivity in the 110°C TL peak (for quartz). This approach was later improved further by alternatively monitoring sensitivity changes in the OSL measured after a ‘test dose’, which is administered immediately after the OSL is measured from the natural and each regenerative dose. This protocol includes internal checks for thermal transfer (recuperation) and for the efficacy of the chosen test dose to correct for sensitivity change, and it also called for a subsequent experiment to test the utility of the protocol to recover a known dose of laboratory radiation, similar in magnitude to what it had absorbed in the environment (the dose recovery test). It has become the standard single-aliquot regenerative-dose (SAR) protocol used today for dating both quartz (Murray and Wintle, 2000, 2003; Wintle and Murray, 2006) and feldspar. Subsequent development has included use of different OSL signals, such as the thermally-transferred OSL signal from quartz, which is discussed below in the context of this paper, to extend the upper age limit of the method.

*Age evaluation and sources of uncertainty*

It is important to recognise that all luminescence dating techniques are inherently experimental. This is because the luminescence characteristics of quartz (and feldspar) vary from site to site, and even within a single site. Preliminary experiments are therefore usually conducted to ascertain the character of the OSL (or TL) signal in order to identify and isolate the most easily bleached thermally-stable component(s) and to identify the most efficient preheat temperature(s). The factors that lead to uncertainty in the determination of a sample’s environmental dose rate are site dependent, and are influenced by uncertainty about a sample’s water content and its burial depth over time, by the degree of knowledge of local variations in the concentrations of relevant radioisotopes in the sediment matrix (on both the macro and micro scales), and how these may have changed over time, and by assumptions made about the degree of equilibrium in their decay chains. There are also uncertainties associated with the radioisotope content within the grains, but this is relatively minor when dating quartz. And of course the fundamental conditions that the mineral grains sampled were exposed to sufficient sunlight prior to burial, and that they have not been mixed with older or younger grain populations after burial, has to be satisfied (or at least accounted for later) and this is not always the case even for aeolian sediments (e.g., Lian and Huntley, 1999; Cohen et al., 2010).

The best check to see if a luminescence dating protocol is able to effectively estimate burial age at a particular site is to compare ages with those derived using reliable independent method at the same stratigraphic position. This was proposed as an acceptance criterion in one of the seminal papers on luminescence dating of sediments (Wintle and Huntley, 1982). In practice, however, this is often difficult to do when working with aeolian landforms, especially dunes, as the applicability of other dating methods to the aeolian environment is rare; however, good consistency has been found in many cases, for example, see Rhodes (2011, fig. 10). Moreover, not all practitioners publish experimental procedures with the same level of detail, and this commonly makes comparison between studies challenging, and differences in ages, even within a single study, difficult to assess. And even in cases where detailed experimental work has been performed, and has been well presented, discrepancies between ages found using different luminescence dating methods can be difficult to understand (e.g., Mueller et al., 2018). It is therefore not possible to conclude that a luminescence dating protocol(s) that has been demonstrated to be successful at one site will also be useful at another site; all that can be said is that it is likely to be successful there as well, sometimes after some modification. These sentiments have been exemplified by Hesse (2016) who provides an analysis of nearly 700 OSL and TL ages, found using various laboratory protocols, using both multiple and single aliquot techniques, associated with Australian continental aeolian dunes (coastal dunes and lunettes were excluded in his review), including those in Tasmania. He did find, however, that the published data sets of age values for this region contained very few internal inconsistencies, such as age reversals (Hesse, 2016).

***Luminescence dating methods relevant to this study***

The geochronology of most sites in Tasmania discussed in this paper come mainly from TL ages derived using the method of Shepherd and Price (1990). Some sites include OSL ages determined using the SAR method (Wintle and Murray, 2000), and one site, Southwood B dune, has been dated using thermally-transferred (TT) OSL signals and the SAR method, which has been shown to be successful in dating sediments that are beyond the upper age limit of more traditional OSL methods.

*The TL method of Shepherd and Price (1990)*

The TL method of Shepherd and Price (1990), which essentially is that described by Readhead (1988), was developed from the early methods described above. It is a combined multiple-aliquot additive and regenerative dose procedure. The TL growth curve in this instance is derived from aliquots that have had the bleachable fractions of their TL signals removed by exposure to an ultraviolet lamp. They are then given, in groups, successively increasing (regenerative) doses of radiation prior to TL measurement. Aliquot-to-aliquot variations in TL intensity is normalised using an “irradiation/second glow” procedure, and TL sensitivity differences between the natural aliquots, and the aliquots that had been bleached in the laboratory, are checked by overlaying the first growth curve (above) with a growth curve generated from natural (unbleached) aliquots that are subsequently given a series of radiation (additive) doses, much like the sensitivity check that is inherent to the AS method. As mentioned earlier, TL ages derived using multiple aliquot techniques require many aliquots of prepared sample to generate a single age. Therefore, TL dating techniques cannot mitigate the adverse effects of poorly bleached grains that may lead to age being overestimated. Thus TL dating is most applicable to well-bleached deposits (loess, and dunes and sandsheets constructed of distally derived material will normally fit this category) and in these instances they have been shown in many cases to yield ages consistent with those found using SAR OSL. In Tasmania, for example, TL ages for dunes at Mary Ann Bay (Slee et al., 2012) determined using the protocol of Shepherd and Price (1990) are consistent with ages found using OSL and what appears to be a SAR method (Shin 2013) (Supplementary Material, Table S1), but unfortunately Shin (2013) provides no experimental detail so a thorough assessment cannot be made.

**Supplementary Material, Table S1.** Comparison of TL and OSL ages obtained from Mary Ann Bay sandsheets. See the main text for details.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Depth (cm) | Laboratory I.D. | Method | Age (ka)1 | Reference |
| 200 | MA02 | OSL | 31.0 ± 3.0 | Shin (2013) |
| 290-300 | W4475 | TL | 30.7 ± 1.0 | Slee et al. (2012) |
| 600 | MA05 | OSL | 25.0 ± 3.0 | Shin (2013) |
| 670-680 | W4476 | TL | 30.3 ± 3.7 | Slee et al. (2012) |

1Errors are ± 1

*Multiple-aliquot OSL and TL dating and single aliquot OSL dating*

Duller and Augustinus (1997) applied three luminescence dating methods to quartz from the Ainslie dunes. The first two procedures consisted of OSL and TL multiple-aliquot methods applied to the same aliquots: the OSL signal was measured first, followed by the TL signal. A single-aliquot OSL procedure was also attempted. The single-aliquot ages were comparable to those found using the multiple-aliquot OSL procedure, and also to three of the five TL ages.

*OSL and TT-OSL dating using SAR*

In light of the development of SAR protocols in the late 1990s (Wintle and Murray, 2000), Duller and Augustinus (2006) re-dated their samples from Ainslie dunes using this method. As mentioned earlier, an important difference between the SAR protocol and the earlier methods used by Duller and Augustinus (1997) is the SAR protocol’s ability to correct for sensitivity change and its inclusion of internal quality control checks. The ages Duller and Augustinus (2006) determined using SAR are significantly different from those found using the older multiple-aliquot methods (Duller and Augustinus, 1997), are considered to be more accurate, and they are also consistent with palaeoclimate interpretations for the region. They also cast doubt on the general applicability of the older methods.

OSL dating using SAR methods with multi-grain aliquots or single grains has become much more routine in Tasmania (see Neudorf et al., 2019, table S1), and an extension of that method that uses the TT-OSL signal, which has been shown to extend the upper age limit of quartz OSL dating (Wang et al., 2006), has been applied at Southwood B dunes (Neudorf et al., 2019). As mentioned earlier, traditional OSL dating protocols involve heating (‘preheating’) the sample to a predefined temperature to empty electrons in thermally unstable traps, and then stimulating the sample with blue light (for quartz) to measure the luminescence resulting from thermally-stable traps. TT-OSL dating, on the other hand, involves heating, then stimulating the sample as one would when using a traditional OSL dating protocol, but then heating the sample again to high temperature (e.g., 290°C) before measuring the luminescence signal a second time. This signal results from the second high-temperature preheat, which thermally transfers charge from less-optically sensitive traps, to optically sensitive traps that are sampled during stimulation (the TT-OSL). For a given quartz sample, growth curves generated by TT-OSL signals continue to increase with added dose when OSL growth curves tend to flatten out (or ‘saturate’), allowing the measurement of equivalent doses from older samples.

At Southwood B, a sequence of TT-OSL SAR ages were found to be consistent with those found previously using the TL dating method of Shepherd and Price (1990), but only after the dosimetry used to derive some of the TL ages was recalculated based on new radioisotope measurements (Neudorf et al., 2019); see also Table 3 and Figure 2 in the main article. Although the apparent consistency between the TL and TT-OSL SAR ages is encouraging, it should be considered with some caution as the TT-OSL SAR dating technique is still relatively novel. Moreover, as the TT-OSL signal bleaches more slowly than the OSL signal it usually requires correction for insufficient bleaching using the signal measured from a modern sample collected from a similar depositional environment.

**NEW TL AGES INCORPORATED INTO THIS REVIEW**

At Rocky Point (39.5985°S 144.0040°E) on the north-east coast of King Island (Figure 2) the age of beach-backing ‘New Dunes’ (Jennings, 1957) exposed within a sandblow within an otherwise vegetated coastal dune complex was investigated. Five units were distinguished by their texture and colour (Figure 2) and units 3 and 5 were sampled for TL dating using rigid opaque PVC tubes 75 mm diameter and 120 mm long. At Maynes Junction (Figure 10) the top and lowest pale layers were sampled for TL analysis by carving a 100 mm3 block of sediment.

TL dating (Supplementary Material, Table S2) was performed using the methods described by Shepherd and Price (1990) and Nanson et al. (1991). Samples were analysed using the 90–125 µm quartz grain size fraction separated from the centre of bulk field samples. A summary of methods employed, including examples of TL glow curves, the TL versus temperature plateaus, and a representative growth curve was presented by McIntosh et al. (2009).

**Supplementary Material, Table S2.** Previously unpublished TL ages for Rocky Point and Maynes Junction aeolian sediments, and data used to derive the TL ages.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
|  | **Rocky Point samples** | | | **Maynes Junction sample** | |
| **Sample Lab No.** | **W5021** | **W5022** | **W5023** | **W4947** | **W4968** |
| **Field ID** | **Unit 3 (upper)** | **Unit 3 (lower)** | **Unit 5** | **Top pale layer** | **Lowest pale layer** |
| TL Plateau region (oC) | 300–400 | 275–500 | 275–500 | 275–500 | 275–500 |
| Analysis temp. (oC) | 375 | 375 | 375 | 375 | 375 |
| Equivalent dose (Gy) | 4.5 ± 0.5 | 5.0 ± 0.5 | 52.2 ± 3.4 | 35.5 ± 2.5 | 176 ± 20 |
| K content (by XRF) (%) | 0.168 ± 0.005 | 0.191 ± 0.005 | 0.249 ± 0.005 | 0.355 ± 0.005 | 0.520 ± 0.005 |
| Moisture content by weight (%) | 3.9 ± 3 | 5.0 ± 3 | 14.0 ± 3 | 11.7 ± 3 | 10.1 ± 3 |
| Specific activity (U+Th) (Bq/kg) | 10.0 ± 0.3 | 19.1 ± 0.6 | 27.5 ± 0.9 | 75.1 ± 2.0 | 71.1 ± 1.7 |
| Cosmic ray contribution (assumed) (µGy/yr) | 180 ± 25 | 180 ± 25 | 180 ± 25 | 150 ± 25 | 150 ± 25 |
| Total environmental dose rate (µGy/yr) | 543 ± 25 | 737 ± 26 | 872 ± 24 | 1813 ± 34 | 1951 ± 32 |
| **TL age** (ka) | **8.32 ± 1.00**1 | **6.75 ± 0.65** | **59.9 ± 4.3** | **19.6 ± 1.4** | **90.2 ± 10.2** |

1This sample exhibited a short temperature plateau suggestive of incomplete re-setting of the TL signal.

*Note*: Measured and calculated values are listed here as reported by the laboratory. Since some of the measured values are reported with a precision of two significant figures, the calculated TL ages should be considered with the same precision.

**PARTICLE SIZE ANALYSIS**

At Maynes Junction, previously radiocarbon dated by McIntosh et al. (2012) a section on the right-hand side of the exposure (Figure 10), including the top pale layer and lowest pale layer was described. Component layers distinguished and sampled on the basis of their texture and colour (National Committee on Soil and Terrain 2009). Air-dried bulk samples were pre-treated as recommended by Cresswell et al. ([2002](file:///C:\Users\p-mcintosh\AppData\Local\Microsoft\Windows\INetCache\Content.Outlook\T9P06MZ1\Bernard%20Walker%20Thesis%20Final.docx#_ENREF_10)). Samples rich in organic matter from 0-12 cm, 12-30 cm, and 70-100 cm depth were treated with H2O2 under gentle heating and disaggregated by addition of 25 ml of 0.05M sodium hexametaphosphate solution followed by 1 min of sonification and overnight end-over-end shaking. Dispersed samples from all sampled layers were separated into fine and coarse fractions using a 63 μm sieve. Sediment and gravel captured on the 63 μm sieve was designated the coarse fraction, and was retained for particle size analysis by dry sieving. The fine fractions were suspended in 1 L sedimentation tubes and particle size analysis was conducted by the pipette method (Cresswell et al. [2002](file:///C:\Users\p-mcintosh\AppData\Local\Microsoft\Windows\INetCache\Content.Outlook\T9P06MZ1\Bernard%20Walker%20Thesis%20Final.docx#_ENREF_10)). A 20 ml blank sample was taken from 25 ml sodium hexametaphosphate in a 1 L sedimentation tube so that a correction for the mass of the dispersant could be applied. The samples were then oven dried overnight at 105˚C and weighed. Coarse fractions (>63 μm) were thoroughly air dried and mechanically shaken through an Endecott standard sieve stack at half phi () intervals for 10 min. Sediment weights obtained by pipette analysis were expressed as a percentage of the total weight of the < 2 mm sample. The percentage of gravel (>2 mm) in the total sample was also calculated.

## **X-RAY FLUORESCENCE ANALYSIS**

Sub-samples of 14–16 g of <2 mm soil from the Maynes Junction soil horizons listed in Table 5 were oven dried and ground to fine powder in a tungsten carbide pneumonic mill. A melted fusion disk was prepared to homogenise the sample and ensure complete oxidation. XRF analysis was performed at the School of Earth Sciences, University of Tasmania using a ScMo 3kW side window X-ray tube and a Philips PW1480 x-ray spectrometer, following the methods of Robinson (2003). Whole rock sample powders were fused with 12–22 flux (a pre-fused mixture consisting of 12 parts Li2B4O7 and 22 parts LiBO2) using a sample: flux ratio of 1:9 at 1100oC. Corrections for mass absorption were calculated using Philips X40 software with De Jongh’s calibration model and Philips’ alpha coefficients.

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