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Muñoz-Salinas, E., Bishop, P., Sanderson, D., and Kinnaird, T. (2014) Using OSL to assess hypotheses related to the impacts of land use change with the early nineteenth century arrival of Europeans in south-eastern Australia: An exploratory case study from Grabben Gullen Creek, New South Wales. Earth Surface Processes and Landforms, 39(12), pp. 1576-1586.

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Deposited on: 7 May 2015.

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Using OSL to assess hypotheses related to the impacts of land use change with the early nineteenth century arrival of Europeans in south-eastern Australia: An exploratory case study from Grabben Gullen Creek, New South Wales

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This article has been accepted for publication and undergone full peer review but has not been through the copyediting, typesetting, pagination and proofreading process, which may lead to differences between this version and the Version of Record. Please cite this article as doi: 10.1002/esp.3542

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ABSTRACT: A common explanation for intense soil erosion and gullying in SE Australia is the introduction by Europeans of new land use practices following their arrival in Australia in the late 18th century. Eucalyptus woodlands were cleared to introduce farming, and valley bottoms, characterized by chains of ponds with organic-rich swampy meadow (SM) soils, were subsequently buried by thick deposits of 'post-settlement alluvium' (PSA) generated by erosion in the catchment. In this study, optically stimulated luminescence (OSL) is used to evaluate the source(s) of the PSA in Grabben Gullen Creek (GGC), Australia. We use a portable OSL reader to measure total photon counts on bulk polymineral and polygrain-size samples from nine profiles along the Creek. We use these luminescence signals as geotracers of sediment source(s) and transport pathways. We obtained higher luminescence signals in the PSA than in the SM sediments, suggesting different sources and fluvial transport conditions for these two widespread sedimentary units. Portable OSL reader data from soils in the GGC catchment that are potential sources for the SM sediments and PSA show that the high luminescence signals recorded in the PSA are similar to those from subsoil samples in granite soils, suggesting that the PSA was derived by gullying of granite subsoils. In the SM sediments, luminescence signals decrease upwards from the base of the profile, as expected in well-reset fluvial deposits, but with one or more changes in gradient in the profile of photon counts with depth, most likely indicating changes in sediment deposition rates. To calculate deposition rates in the SM sediments, several samples were dated using OSL. The OSL ages produced low scatter in the equivalent doses, confirming the well-reset nature of the grains composing the SM and

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indicating a process of sediment transport in dilute flows, as is interpreted from the portable OSL signals.

Keywords: land degradation, post-settlement alluvium, swampy meadow, OSL, Australia

Introduction

Toy *et al.* (2002) have commented that, "on the basis of its temporal and spatial uniquity, erosion qualifies as a major, quite possibly *the* major, environmental problem worldwide" (p.1; their emphasis). And as the population of the Earth passes 7 billion, extensive areas of the Earth's surface face ever-increasing pressure, land degradation and concomitant loss of agricultural productivity. Montgomery (2007) noted that as societies develop, they tend to over-exploit their soil resource, and that that over-exploitation may then be implicated in the society's subsequent demise. A key element in this multi-faceted debate about the causes of land degradation is the interaction between climatic pressures on land cover and soils, and changes in land use to more intensive agriculture, especially when that involves a change from lower intensity subsistence types of land use to more intensive European-style agriculture (Montgomery, 2007, Chapter 5). This issue is particularly pertinent to understanding land use, land use change and land degradation in Australia, one of the more recently colonised regions. The late 18^{th} century arrival of Europeans is thought to have triggered major land use change in which the indigenous Australians' subsistence hunting and

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gathering, often involving burning of the native vegetation to promote fresh growth to encourage game into an area and to drive that game for hunting, was progressively supplanted by widespread clearing for European-style arable farming and/or livestock grazing. The exact nature of the post-European land use depended on a particular area's soil, topography and climate but the impacts are interpreted to have been profound and long-lasting, be they in the semi-arid and arid interior (e.g., Heathcote, 1965; Condon, 2002) or in the 'better-watered' inland fringes of the continent (Figure 1).

The work we report here is from that better-watered fringe, on the Southern Tablelands of the state of New South Wales (NSW) in inland southeastern Australia. Eyles (1977) used the field records of the first European explorers to reconstruct the landscape of the Southern Tablelands when Europeans first moved into the area. At the time of this first European incursion, valley bottoms in inland SE Australia were typically swampy and drained by 'chains of ponds', connected, if at all, by diffuse, low velocity channels (Eyles, 1977; Prosser *et al*., 1944; Brierley and Fryirs, 1999). It is generally argued that landscapes were eroding slowly and were not extensively gullied or in other ways substantially disturbed. Conventional wisdom is that the Europeans' clearing of native vegetation led to major geomorphological impacts (e.g., Eyles, 1977; Prosser, 1991; Wasson *et al.,* 1998; Rustomji and Pietsch, 2007): rivers incised their beds, and gullies cut back up drainage lines, generating the high volumes of sediment known as post-contact sediment or post-settlement alluvium (PSA) (e.g., Wasson *et al.,* 1998; Muñoz-Salinas *et al*., 2011). Such sediment still blankets many valley

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bottoms of inland SE Australia and is clearly identifiable in river-bank exposures as a sandy and gravelly sheet deposit overlying the finer-grained organic-rich swampy meadow (SM) deposits of the pre-European chains of ponds (Prosser, 1991; Wasson *et al.,* 1998) (Figure 2).

Butzer and Helgren (2005) have recently questioned this interpretation, using diaries and observations of early explorers and surveyors to argue that inland SE Australia may have been quite extensively gullied and 'disturbed' when Europeans arrived. It is clear that the Pleistocene and Holocene in SE Australia were marked by episodic phases of aggradation and degradation (gullying), triggered by climatic controls and/or threshold-crossing catchment changes and/or indigenous land use practices (e.g., Chappel, 1991; Prosser and et al., 1994; Zierholz *et al*., 2001; Eriksson *et al*, 2006). Some of these late Quaternary aggradational phases lasted for several thousand years and ended with gullying associated with, it is argued, high magnitude climatic events (Chappel, 1991; Prosser *et al*., 1994; Eriksson *et al*, 2006). On the other hand, Butzer and Helgren (2005) have suggested that native Australians, arriving in Australia ~50ka (Rasmussen *et al.,* 2011), had a significant impact on riverine landscapes when they used burning to clear forests and woodland, triggering landscape degradation by gullying. This interpretation implies that some PSA in fact pre-dates the arrival of Europeans. Resolution of the timing and nature of the catchment disturbance recorded by supposed PSA is important on several fronts, including: understanding the nature of 'natural' landscapes; quantifying the disturbance impact of 'European' agricultural practices on landscapes; and re-assessing the nature and impact of traditional indigenous land practices. These

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questions have broad implications and arise in all landscapes where major changes in land use have occurred (or will occur). The work reported here relates to PSA along the lower Grabben Gullen Creek (GGC), a right-bank tributary of the Lachlan River that joins the Lachlan between the village of Dalton and the locality of Bevandale. We address two hypotheses:

i. That PSA was derived by gullying of catchment soils, including subsoils, as implied by many including Wasson *et al*. (1998), and not by processes such as sheet erosion of topsoil; and
ii. That PSA consists of sediments transported by turbid flows, in contrast to the SM, which is composed of sediments transported in dilute flows.

We use the term PSA without age connotation, to refer to the widespread mantle of medium- to coarse-grained sediment that commonly overlies SM materials in inland SE Australia. The work builds on our preliminary data on PSA in GGC, which used optically stimulated luminescence (OSL) in a different way from its more common use as a dating tool (Muñoz-Salinas *et al*., 2011). That preliminary work demonstrated that the PSA material had not been well exposed to sunlight prior to its deposition and that the SM sediment had been well bleached of its luminescence prior to deposition. The SM material is thus potentially datable by the OSL technique, unlike the PSA we studied (Muñoz-Salinas *et al*., 2011). In the present study, we use OSL as a geotracer to determine provenance of the PSA in the lower GGC for the first time, as well as a tool to date the SM.

Study area

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GGC rises on the continental drainage divide in central NSW and flows west to the Lachlan. The Lachlan is a major tributary of the 1M km^2 Murray-Darling system that drains the inland flank of the 'Great Dividing Range' of eastern Australia, which is a high elevation passive continental margin (Figure 3A) (Bishop and Goldrick, 2000; Persano *et al*., 2005).

The Lachlan catchment is formed on alternating meridional belts of regional grade metasediments and granites, which have locally contact-metamorphosed the adjacent metasediments. These contact metamorphic zones commonly form lines of hills adjacent to the intruding granites (e.g., where GGC flows westwards off the granites in its upper reaches onto the metasediments of its lower reaches before joining the Lachlan).

The vegetation of the study area has been extensively cleared, especially on the granitic soils. Small patches of thin scrubby woodland are found on the soils formed on metasediments, particularly on the thin, low nutrient soils on the contact metamorphic rocks. It is unclear whether these patches of woodland are uncleared remnants of the original vegetation or are areas of re-growth. The original vegetation is likely to have been *Eucalyptus* forest on the granitic soils, with less dense forest and woodland, again dominated by *Eucalyptus* species, on metasediment soils. Bayley's (1975) unverified account of the vegetation prior to the European settlers' clearing of the granite country in the upper parts of GGC highlights forests of white box (*E. albens*) and yellow box (*E. melliodora*).

These early European settlers first arrived in the area in the 1820s (Bayley, 1975), attracted by appropriate soils and rainfalls for livestock grazing (mean annual rainfall 1981-2010 of ~640 mm; Goulburn station, NSW,

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34.75ºS, 149.73ºE; Bureau of Meteorology Australian Government, 2011). Bayley (1975) has also noted that grain crops were cultivated in the area when the Europeans first arrived, but that land use evolved into the sheep farming and more minor cattle grazing that still characterise the area.

GGC rises at 890 m asl close to the continental drainage divide on Late Palaeozoic granites and flows for ~40 km across these granites and then across Late Palaeozoic metasediments to its confluence with the Lachlan at 500 m asl (Figure 3B). The last 7 km of its course, across the meridionally striking metasediments, would have been through valley-bottom chains of ponds, which seem commonly to have formed upstream of outcrops of steeply dipping, more resistant metasediments. The PSA deposits can be observed along the full length of these lower reaches of the creek, and more sporadically along its upper reaches on granitic rocks.

Methods

We used three luminescence techniques in this exploratory assessment of provenance and age of profiles in the riverbanks of GGC. These techniques were:

1. net photon counts on bulk polymineral and polygrain-size sediment samples, using the SUERC portable OSL reader (Sanderson and Murphy, 2010; cf. Muñoz-Salinas *et al*., 2011; 2012);
2. laboratory measurement of OSL profiling samples (Burbidge *et al*., 2007); and
3. full quartz OSL SAR dating (see Sanderson *et al*., 2007).

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In light of the unbleached nature of the PSA that was revealed by the portable reader data (see below and Muñoz-Salinas *et al.*'s (2011) preliminary data), the profiling and dating samples were collected from the material underlying the PSA, mainly corresponding to the SM deposit, and were analysed at the SUERC luminescence laboratory.

Prior to the field sampling, we reconnoitred the lower 7 km of GGC, where it flows across metasediments to its confluence with the Lachlan, as well as several upper reaches in the granite areas, upstream of the steep knickpoint that marks the fall of GGC from the granite to the metasediments (Figure 3B). We sampled profiles where there was unambiguous outcrop of PSA overlying SM with a planar and apparently non-erosive contact. At the river-bank profiles selected for sampling, we shielded the profile against the sunlight with dark cloth and cleaned back the profile for ~5cm. We then sampled the sediment in tubes ~2 cm in diameter and 5 cm long. For the portable OSL reader analyses, we used the portable reader in a dark room and under safe light. We stimulated each sample using infrared luminescence (IRSL) for two 30 s periods separated by 10 s of dark counts with the sample in the sample tray, followed by the same stimulation sequence using blue light (BLSL), giving 60 s of counting in each wavelength for each sample. Each of the two measurement cycles was preceded and followed by 10 s dark counts. We sampled nine portable OSL reader profiles in the PSA sediments, eight in the valley-bottom metasediments area, where we assume that chains of ponds characterised the valley bottoms before their SM materials were overlain by the PSA, and one from the upstream, granite areas. We also sampled three soil profiles (topsoil and subsoil) on the slopes/valley sides on

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metasediments in the lower GGC, and two soil profiles on granite in the upper part of the catchment. The aim of the sampling of the soil profiles was to use luminescence to assess likely sources of the PSA.

We used the portable reader luminescence signals to select one of the nine profiles to sample for the OSL profiling and dating (see Munyikwa *et al*.'s (2012) use of a similar approach). The profile was chosen because its portable OSL reader data show the typically high luminescence signals in the PSA, immediately overlying the top of the SM materials, which display low signals that increase regularly with depth, as is commonly found in the SM materials (Figure 4). This steady upward decrease in luminescence signals in the SM indicates that the material was well-bleached prior to deposition (see Muñoz-Salinas et al., 2011), and hence is suitable for full OSL dating (Figure 4). The material underlying the SM deposit (termed here 'pre-SM') has lower luminescence signals suggesting different sedimentation processes for this material, different material with different luminescence sensitivities, different dose rates and/or other factors.

In the profile selected for more detailed analysis, we extracted eight samples, five for OSL profiling (SUTL2357A, SUTL2357B, SUTL2357C, SUTL2357D and SUTL2357E) and three for full OSL dating (SUTL2354, SUTL2355 and SUTL2356), following the approach of Burbidge et al. (2007) and Sanderson et al. (2007) (Figure 5). In effect, this approach measures the stored dose (equivalent dose) in each of the eight samples and uses the dose rates determined for adjacent full dating samples to estimate apparent luminescence ages (ages of enclosure) for each of the profiling samples. This approach enabled a preliminary chronology to be established for the profiling

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samples.

For the full OSL dating we collected one sample of the pre-SM sediments and two of the SM sediments, using tubes ~10 cm in diameter and 30 cm long under shaded conditions (Figure 5). Approximately 10-15 g of the material extracted from the core of the tubes was sieved between 90-250 μm. The resulting material was treated using 1 M HCl and 40% HF to dissolve carbonates and any precipitated fluoride, and sodium polytungstate solutions were used to separate quartz and feldspar. Sixteen single aliquots were prepared from the resulting material each consisting of a few grains c. 5-15 mg each in total) mounted on stainless steel disks. The single aliquot regenerative (SAR) method (Murray and Wintle, 2000; Wintle and Murray, 2006) was used to analyse this material in the SUERC luminescence laboratory, to obtain equivalent doses on each sample's 16 aliquots of sand-sized quartz. A portable gamma spectrometer was used in the field to estimate the environmental dose rate for the three dating samples and ~500 g of bulk sediment surrounding the sample, plus the materials from the dating tube samples, were subsequently analysed at SUERC for full beta and gamma spectrometry to obtain the dose rates needed to calculate the sediment age (Huntley *et al*., 1985; Wintle, 1997; Aitken, 1998).

The profiling samples were extracted from the sunlight-shaded profile, using ~3 cm diameter, ~10 cm long tubes. Etched quartz and polymineral separates were obtained for each of the profiling samples using the methods outlined by Burbidge et al. (2007). Paired aliquots from each profiling position were subjected to simple single-aliquot dose determinations, calculated relative to a single regenerative dose of 5 Gy, normalised to a 1 Gy test dose.

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For four of the five profiling samples (241, 145, 127 and 77 cm depths), the total dose rate was estimated from the adjacent full-dating samples; for the fifth sample (183 cm), the total dose rate was estimated by interpolation between the two closest dating locations. Initially, age estimates were calculated for each set of paired aliquots, by combining the linear extrapolated stored dose estimates with the dose rates estimated for each position. To account for the non-linear dose response curve obtained for the dating samples, the normalised OSL values obtained for each profiling position were fitted to a composite dose response curve generated from the equivalent full dating sample (Figure 6). The close proximity of the full dating and profiling samples, and the uniformity of the dose rates, justify this approach.

For calculating equivalent dose determinations for the full OSL dating, data from SAR dose measurements were analysed using the Risø TL/OSL Viewer programme to export integrated summary files that were analysed in MS Excel and SigmaPlot. Dose response curves for each of the four pre-heating temperature groups and the combined data were determined using a fit to a saturating exponential function (Figure 7). The equivalent dose is then determined for each aliquot using the corresponding exponential fit parameters (Figure 7).

The calculation of the effective dose rate in the full OSL dating is presented in Table 2. The total dose rate is determined from the sum of the effective beta and gamma dose rates, and the cosmic dose rate. Age estimates are determined by dividing the equivalent stored dose by the dose rate. Uncertainty on the age estimates is given by combination of the

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uncertainty on the dose rates and stored doses, with an additional 5% external error.

The total dose rates for the profiling ages (i.e. samples at 241, 145, 127 and 77 cm) were estimated from adjacent tube sample locations. For the profiling sample at 183 cm, the total dose rate was estimated by interpolation between tube locations 215 and 163 cm. Equivalent dose determinations for each of the quartz profiling aliquots were initially scaled to the single regenerative dose of 5 Gy. Apparent age estimates were then calculated combining these linear extrapolated dose estimates with the dose rates for each position. This method slightly underestimates the apparent dose for each of the quartz profiling aliquots, as composite dose response curves generated for the full dating samples are known to grow exponentially with regeneration dose.

To improve the initial estimates, and take account of the non-linear dose response curve for the samples, the following procedure was followed. Normalised ratios were scaled to account for the test dose change between the full SAR (2 Gy) and profiling (1 Gy) measurements. These normalised values were then fitted to a composite dose response curve generated from the full dating samples. Normalised OSL values for the 5 Gy regenerative points from each of the profiling samples, when scaled to account for the test dose change, plot on the composite dose response curve (Fig. 7).

Results

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Portable OSL reader results

The BLSL and IRSL signals from the PSA-SM profiles and the metasediment and granite soil profiles are given in Figure 8. The BLSL and IRSL signals in the SM sediments exhibit the regular upward decline found in our preliminary study of the SM-PSA (Munoz-Salinas *et al.*, 2011). We interpret this steady upward decrease in signal to mean that the sediment was deposited in the valley-bottom SM by low energy transport processes and that the SM sediment was well-bleached prior to deposition. The portable reader luminescence signal thus reflects post-depositional in-growth of luminescence in grains that were well-bleached (zeroed) at deposition.

The luminescence signals in the basal PSA sample are abruptly higher than the values in the top SM sample, signalling a major and abrupt change in provenance and/or transport dynamics in the switch to PSA sedimentation. The BLSL and IRSL luminescence signals in the PSA are overall several thousand counts higher than the signals from the upper SM sediments, as was also found in our preliminary work (Munoz-Salinas *et al*., 2011). The higher luminescence signals in the PSA relative to the SM cannot reflect greater post-depositional ingrowth of luminescence in the PSA because (i) the PSA has been deposited for a shorter time than the SM, and (ii) the dose rates in the PSA, measured using the field dosimeter, are comparable to, or even lower than, the dose rates in the SM. The PSA's higher luminescence signals are likely to be related to several factors, including: (i) a high stored dose in the sediments deposited in the PSA, prior to that sediment's initial

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detachment from its 'parent' soils and transport through the catchment; (ii) incomplete bleaching of those sediments during fluvial transport; (iii) grain-size effects, the PSA (2% clay, 17 % silt and 81 % sand) containing coarser grains than the SM (3% clay, 19% silt and 78% sand) and coarser grains have been sometimes found to be less reset than finer sediment (e.g., Bishop et al., 2010); and (iv) important differences in constituent mineralogies in the PSA compared to the SM.

The portable reader luminescence data confirm that the PSA was unbleached (or at best heterogeneously bleached) prior to deposition and that small aliquot OSL procedures are therefore inappropriate to date the deposition of the PSA. On the other hand, OSL dating is appropriate for the SM.

Regular OSL dating results

The ages from the full OSL dating and profiling are presented in Table 1. An age of 5.66 ± 0.43 ka was obtained for the lower sample (the pre-SM deposit); an age of 5.17 ± 0.30 ka was obtained for the middle sample (SM); and an age of 2.43 ± 0.14 ka was obtained for the upper sample (SM deposit). Note that the age estimates for the pre-SM and lower SM deposits are similar, indicative that there was no break in sedimentation across the boundary.

Ages calculated for the profiling samples were as follows: 4.56 ± 0.40, 4.48 ± 0.34, 3.87 ± 0.52, 3.36 ± 0.18 and 1.05 ± 0.06 ka (uncertainty = standard deviation between aliquots). When considered together with the quartz SAR

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dates, the profiling apparent ages indicate that there are two age inversions in the lower part of the succession, between 241 and 215 cm, and 183 and 163 cm.

The full-OSL and profiling ages between the 103 cm and 163 cm depths yield inter-sample sedimentation rates of 0.18, 0.27, 0.35 and 0.14 mm/a (Table 1).

Discussion

Using luminescence signals as a geotracer of the post-settlement alluvium

The nine PSA profiles investigated along GGC have different thicknesses, luminescence magnitudes and luminescence patterns, and there appears to be no pattern in the depth of peak luminescence values (Figure 8). On the other hand, the luminescence values from the metasediment and granite soil profiles are always lower in the shallower soil (i.e., in the topsoil and shallow subsoil) (Figure 8). Such a depth distribution of luminescence signals is consistent with luminescence data from soils elsewhere on the SE Australian Tablelands. Heimsath *et al*. (2002), for example, have shown that between a half and two thirds of grains from the topsoil and shallow subsoil in soil profiles in a small catchment in southeastern NSW exhibit finite OSL ages and have been at the ground surface in the last 10-15 ka; deeper parts of the profile have higher proportions of grains that have not been at the ground surface recently, if at all. Thus, the generally lower luminescence signals in the

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shallower soil layers in this study are most likely related to the repeated movement of soil material to the ground surface by bioturbation by soil fauna and tree throw (cf. Humphreys, 1994; Paton *et al*., 1995). We interpret the higher luminescence signals in the PSA to indicate that the PSA is likely to have been derived by erosion of deeper subsoil materials and perhaps, therefore, to have been derived largely by gullying into subsoils.

Maximum IRSL and BLSL signals are lower in metasediment subsoils than in the PSA (Figure 9). These data confirm that the PSA exhibiting the highest luminescence signals (hundreds of thousands to millions of photon counts) cannot have been derived from the metasediment soils (maximum portable reader signals of tens of thousands of counts). The maximum luminescence signals recorded for the granite subsoils – millions to tens of millions of counts – are higher than the PSA luminescence peaks (Figure 9). We interpret these data to mean that the PSA with the highest luminescence signals was likely derived by erosion of granite subsoils, with the lower maximum luminescence signals in the PSA compared to the granite signals indicating post-detachment partial bleaching of granite-derived sediments and/or mixing of metasediment-derived sediments into the PSA.

This model of progressive downstream mixing of sediment from different sources and/or with different luminescence signals is consistent with the decline in maximum IRSL and BLSL signals in the PSA (Figure 10 and Table 3). These data indicate that sediment eroded from the granite areas and transported by GGC is exposed to sunlight that partially bleaches the sediment in transport and, as well, that sediment derived from metasediment soils, with a lower signal, is admixed into that sediment as it moves through

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the lower reaches of the creek.

OSL dating

The full age determinations SUTL2355 and 2356 and the ages based on the OSL profiling samples in the upper ~1 m of the SM show a tight linear trend with depth (Figure 11), to which the age determination on the pre-SM material, SUTL2354, does not fit (as is hinted at by portable reader values – Figure 4 and Table 1). The sedimentation rates in the SM deposit vary slightly with depth, averaging about 0.3 mm/a (Table 1). A regression line fitted to the upper metre of the SM profiling samples and full age samples provides an age-depth profile of the SM sediments (Figure 11). Projecting the regression line in Figure 11 to the contact between the SM and the PSA at 61 cm depth yields an age of 378 a, implying that the onset of PSA sedimentation pre-dated the early to mid-19th century arrival of Europeans in the upper Lachlan. If this age is accepted, then cessation of PSA sedimentation and subsequent river incision occurred some time in the last ~400 years. Eyles (1977) used early surveyors' records to note that gullies were present in the NSW Southern and Central Tablelands at the arrival of Europeans, as did Butzer and Helgren (2005) (this is the basis of the latter's argument). It is therefore possible that incision of GGC and abandonment of the upper surface of a thick deposit of PSA pre-dated European arrival. If, on the other hand, it is accepted that the incision of upper GGC and the associated blanketing of the lower reaches with sandy bedload, followed by incision of those lower reaches to leave the PSA perched above the river, post-dated European arrival, that

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sequence of events must have occurred between the early to mid-19th century and 1950 (cf. Eyles's (1977) conclusion to this effect). In that case, the PSA deposit formed at a sedimentation rate of between 1.7 mm.a^{-1} and 2.4 mm.a^{-1}. The rate of deposition of the PSA is thus an order of magnitude higher than the deposition rates in the SM.

The interpretation that landscape degradational (erosional) processes and deposition of PSA in GGC started ~380 years ago, almost 200 years before Europeans' early to mid-19th century arrival in the area relies on projecting the age-depth profile in the SM unit to the contact between the SM and the PSA. The possibility of erosion of the upper part of the SM deposit before initiation of the PSA sedimentation, and hence truncation of the SM age-depth profile, cannot be dismissed, but the generally planar or gently undulating geometry of the contact between the SM and the overlying PSA, and the lack of rip-up clasts of SM sediment in the basal layers of the PSA, are both suggestive that the base of the PSA at the GGC-P3 dating site is non-erosive. If deposition of the PSA did begin ~380 years ago, the unit cannot of course be 'post-settlement' or post-European. The hypothesis of erosive processes associated with native Australian burning practices (as proposed by Butzer and Helgren, 2005) is consistent with our results and with descriptions of the first explorers, who recorded localities with entrenched rivers (Eyles, 1977). The implication of our results is not, of course, that all PSA is 'pre-European' – Rustomji and Pietsch's (2007) extensive data demonstrate that many PSA deposits are indeed post-European – but that PSA is likely to have a range of ages, depending on local soils and vegetation, the nature and intensity of land use, both pre- and post-European,

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and the climatic conditions when the Europeans arrived. Our results indicate that it is invalid simply to assume that a layer of 'PSA' that blankets lower hillslopes and valley bottoms is post-European.

Conclusions

Portable OSL reader results from the nine profiles on the PSA and SM deposits located in GGC exhibit luminescence signals in the younger PSA several hundreds of counts higher than those luminescence signals from the older SM deposit. This finding confirms the findings of our preliminary study (Muñoz-Salinas et al., 2011). The high luminescence signals in the PSA indicate that poorly-reset material was deposited after the disturbance of the natural environment. The pattern of the luminescence signals in different soils in the GGC catchment indicates that the principal source of the PSA deposit is the granite subsoils in the upper part of the catchment.

The successful use of luminescence portable OSL reader signals to identify the source of fluvial deposits means that the portable OSL reader luminescence signals may be used in favourable circumstance as geotracers to identify sediment sources. Interestingly, this new use of OSL relies on the fact that the sediment is poorly-reset and perhaps of limited use for OSL dating.

Portable OSL luminescence signals from the SM deposit indicate that this deposit is composed of well-reset grains that allow full OSL dating. Full OSL dating and profiling were used to obtain ages through the SM deposit. Full OSL ages obtained from SAR method using 16 aliquots indicate

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equivalent doses with low scattering confirming that the sediment is well-reset in terms of uminescence. Ages from the SM range between 1 ka and 5 ka and indicate depositional rates between 0.1-04 mm/a. The age of the base of the PSA could not be unequivocally established, although the age-depth model of OSL ages indicates a basal age of the PSA of ~400 a. This result prompts intriguing questions about natural landscape processes and human impact on those processes prior to the arrival of Europeans in the late 18th century.

Acknowledgements–A European Union-funded Marie Curie Intra-European Fellowship to the first author provided funds to carry out this research. The authors thank Rob and Marg Murray of 'Bevandale' for their kind hospitality during field work, and the McGaw family of 'Abbeyville' for permitting access to Grabben Gullen Creek. Very special thanks go to Meredith Orr for field assistance.

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Table 1. OSL dating and laboratory profiling data for the GGC-P3 profile on Grabben Gullen Creek.

SUERC lab number/ field sample number	Stratigraphic unit	Depth from present ground surface /cm	No. of aliquots	Average weight / mg	SAR acceptance criteria: Sensitivity / counts per Gy	SAR acceptance criteria: Sensitivity change per cycle /%	SAR acceptance criteria: Zero dose /Gy	SAR acceptance criteria: IRSL response /%	Stored dose /Gy	Dose rate /mGya^{-1}	*Age* /ka	Depositional rates /mm a^{-1}
SUTL2357E**	SM	77	2						2.49±0.01	2.38±0.13	1.05±0.06	
SUTL2356 / SUTLOSL3*	SM	103	16	9.1	31082 ± 2671	4.6 ± 1.8	0.18 ± 0.14	4.96 ± 1.30	5.84±0.15	2.38±0.13	2.43±0.14	0.18
SUTL2357D**	SM	127	2						7.99±0.04	2.38±0.13	3.36±0.18	0.27
SUTL2357C**	SM	145	2						9.32±1.14	2.41±0.14	3.87±0.52	0.35
SUTL2355 / OSL2*	SM	163	16	7.9	28903 ± 2671	3.1 ± 1.8	0.35 ± 0.34	2.84 ± 0.89	12.46±0.10	2.41±0.14	5.17±0.30	0.14
SUTL2357B**	Pre -SM	183	2						10.47±0.21	2.29±0.17	4.48±0.34	
SUTL2354 / OSL1*	Pre -SM	215	16	7.5	31082 ± 2671	3.9 ± 1.7	0.07 ± 0.09	2.02 ± 0.26	12.96±0.17	2.29±0.17	5.66±0.43	
SUTL2357A**	Pre -SM	241	2						10.45±0.50	2.29±0.17	4.56±0.40	

* OSL dating sample with full field and laboratory dosimetry determinations

** OSL profiling sample, with ages calculated using dosimetry of the adjacent full dating sample(s)

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Table 2. Effective beta and gamma dose rates.

Effective dose rates (mGy a^{-1})		
Beta[a]	Gamma	Total[b]
1.34±0.09	0.76±0.14	2.29±0.17
1.38±0.10	0.84±0.08	2.41±0.14
1.34±0.09	0.85±0.08	2.38±0.13

[a]Effective beta dose rate combining water content corrections with inverse grain size attenuation factors obtained by weighting the 200μm attenuation factors of Mejdahl (1979) for K, U and Th by the relative beta dose contributions for each source determined by Gamma Spectrometry.
[b]Including a cosmic ray dose-rate contribution -0.183±0.05, based on Prescott and Hutton (1994)

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Table 3. Distance from PSA profiles to the Grabben Gullen Creek mouth with maximum values of luminescence signals on IRSL and BLSL.

PSA profiles at Grabben Gullen Creek	Distance to Grabben Gullen Creek mouth (km)	Max. IRSL (total photon counts)	Max. BLSL (total photon counts)
GGC-P10	8.32	2671882	17779701
GGC-P1	2.93	2615487	6961598
GGC-P2	2.63	2106660	4230837
GGC-P3	2.31	1117449	2307892
GGC-P4	1.37	158341	322060
GGC-P0	1.24	431998	1261650
GGC-P8	1.02	706672	1329937
GGC-P7	0.92	528448	428767
GGC-P6	0.77	1102480	2202241

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Figure 1. The upper Lachlan River near Bulley's Crossing, south of the confluence of Grabben Gullen Creek (this study's focus) with the Lachlan. The bed of the Lachlan here has been blanketed by sandy sediment, which likely followed European settlement. The latter is indicated by anecdotal evidence to the second author from a 70-year old local farmer, three decades ago. The farmer observed that when he was a young boy growing up in the general area shown in this photograph, the Lachlan was a bedrock river characterised by deep pools separated by bedrock bars, strongly indicating that the thick sediment blanketing the bed of the Lachlan has moved into and down the Lachlan in the last 100 years or so, following catchment clearing and the introduction of sheep grazing. The flat-topped hill on the skyline is capped by a 21 Myr-old valley-filling lava that flowed in the same direction as the modern Lachlan (i.e., northwards, to the left). The height difference between the basalt remnant and the modern river gives a long-term (Neogene) rate of erosion/denudation in the Lachlan of ~5 m Myr^{-1} (Bishop *et al*., 1985).

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Figure 2. A typical riverbank profile on Gullen Grabben Creek showing the post-settlement alluvium (PSA) overlying swampy meadow sediments (SM). The height difference between the top of the PSA and the current river bed is a measure of post-PSA incision.

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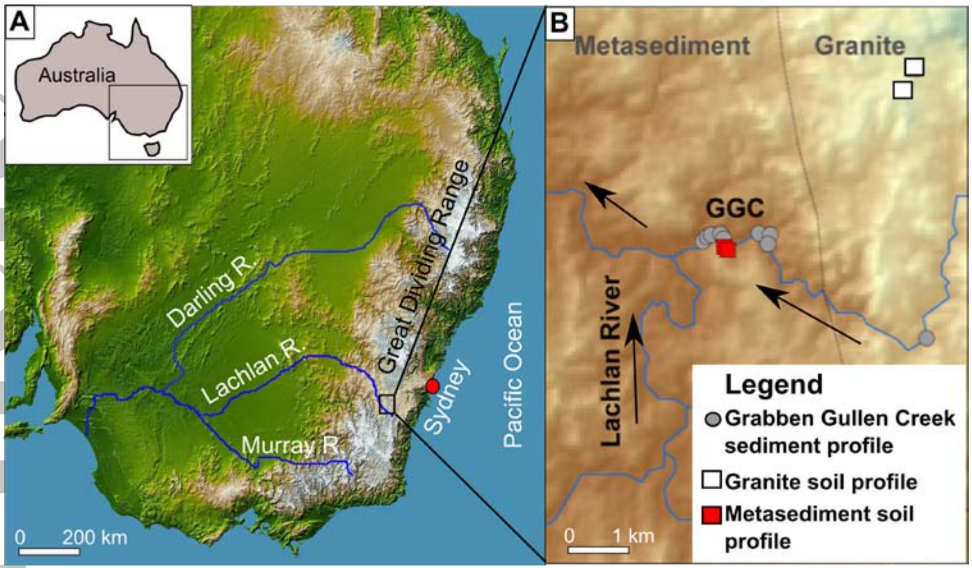

Figure 3. Location of Grabben Gullen Creek in Australia. A.The creek is a tributary of the Lachlan river, which is part of the Murray-Darling river system. The creek rises at the continental drainage divide. B. Location of all portable OSL reader profiles measured through PSA in Grabben Gullen Creek (labelled in the figure as GGC) and through soil profiles in the metasediment and granite areas.

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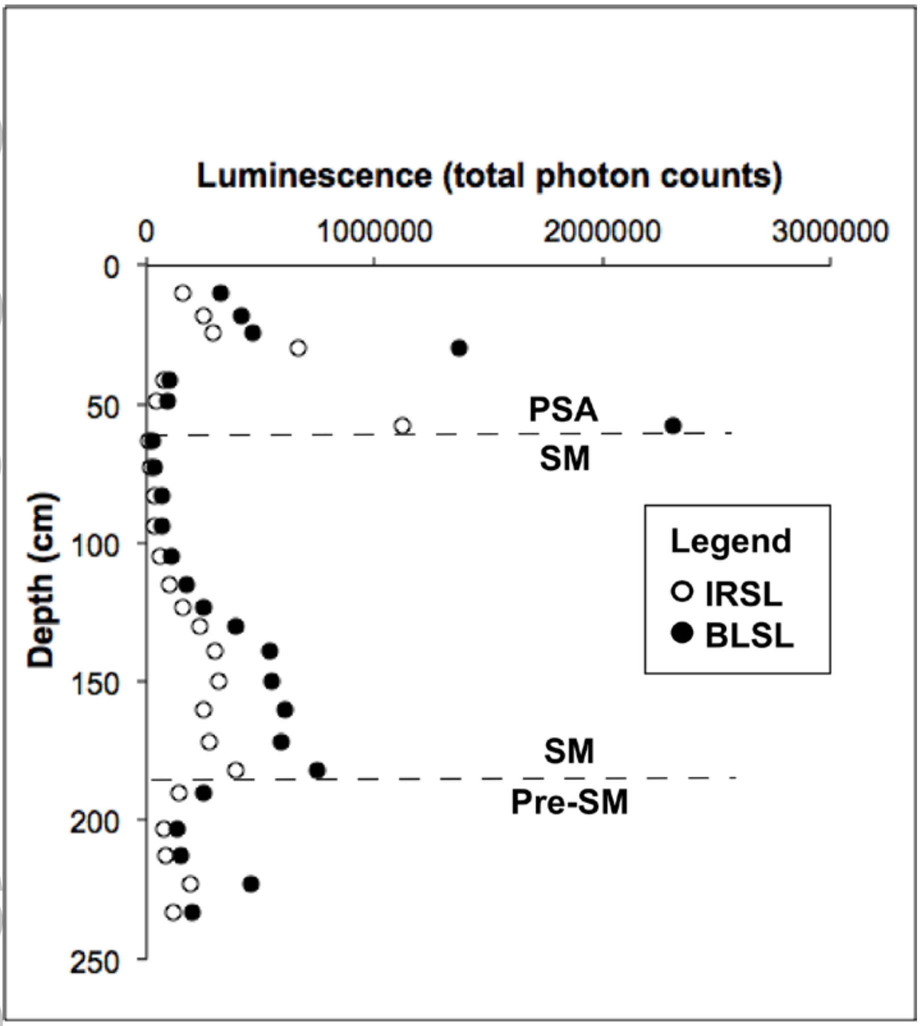

Figure 4. Plot of portable OSL reader luminescence signals (at profile GGC-P3), showing a steady upwards decline in signal in the SM, which is interpreted to reflect post-depositional ingrowth of luminescence in the steady deposition of well-bleached (zeroed) sediments that are thus suitable for OSL dating (see also Muñoz-Salinas *et al*., 2011). Portable reader luminescence signals are generally higher in the PSA than in the SM, and indicate the deposition of unbleached or partially bleached sediment to form the PSA, which is thus to be avoided for OSL dating by the small aliquot method used here. The pre-SM material at the base of the profile has lower more random luminescence signals.

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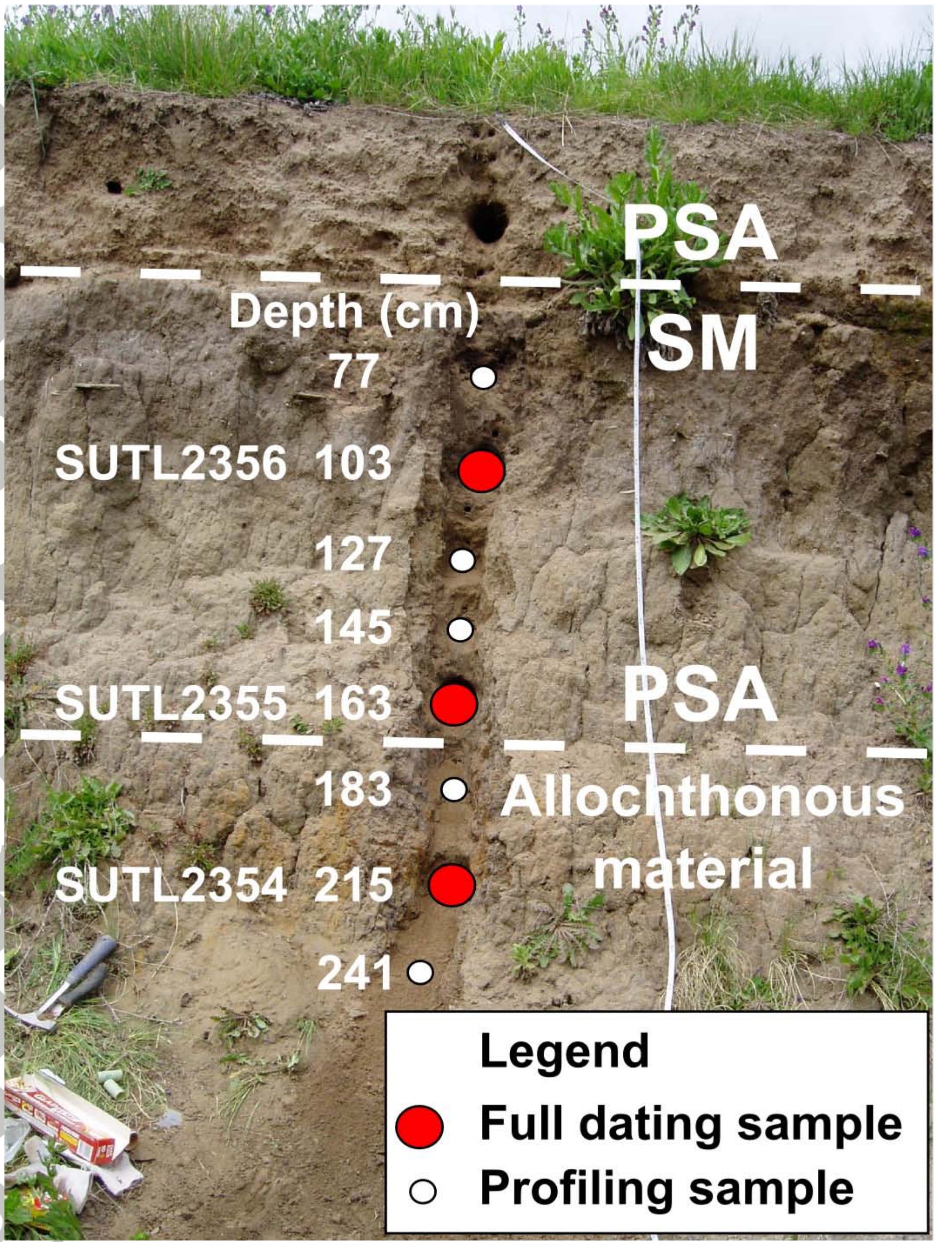

Figure 5. The OSL dating profile (GGC-P3) in Grabben Gullen Creek, indicating the sample points for the OSL profiling samples, and the full OSL dating samples in the SM and allochthonous material.

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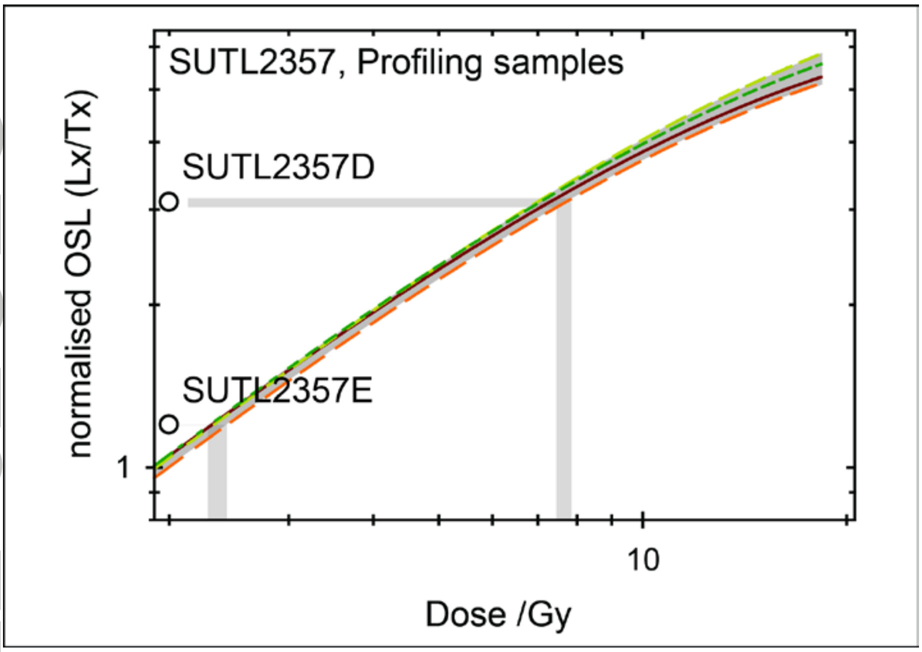

Figure 6. Profiling measurements fitted to the composite dose response curve of SUTL2356; the profiling samples are taken from positions either side of the full dating sample.

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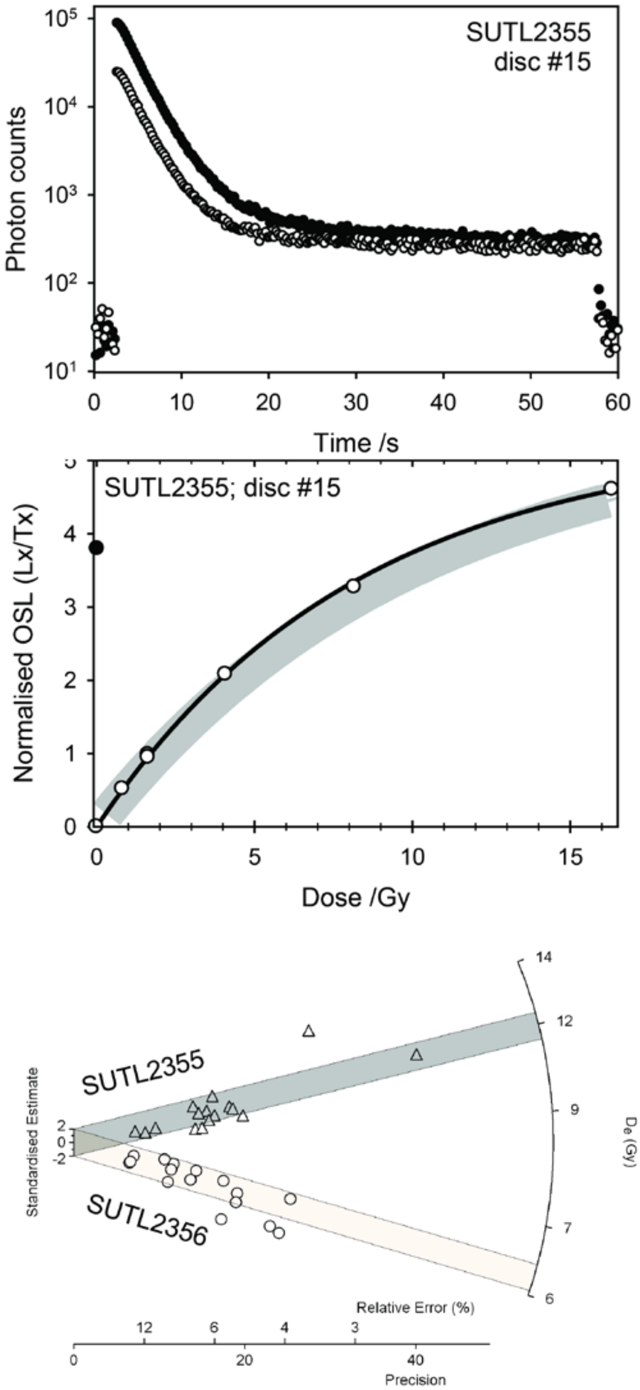

Figure 7. (a) Typical decay curve for SUTL2355; shown are the natural and 1Gy test dose responses; (b) Representative dose response curve for a single aliquot of the same sample; the composite dose response curve obtained for the sixteen aliquot set is shown as the grey line; (c) Radial plots showing the distribution in equivalent dose estimates for SUTL2355 and SUTL2356.

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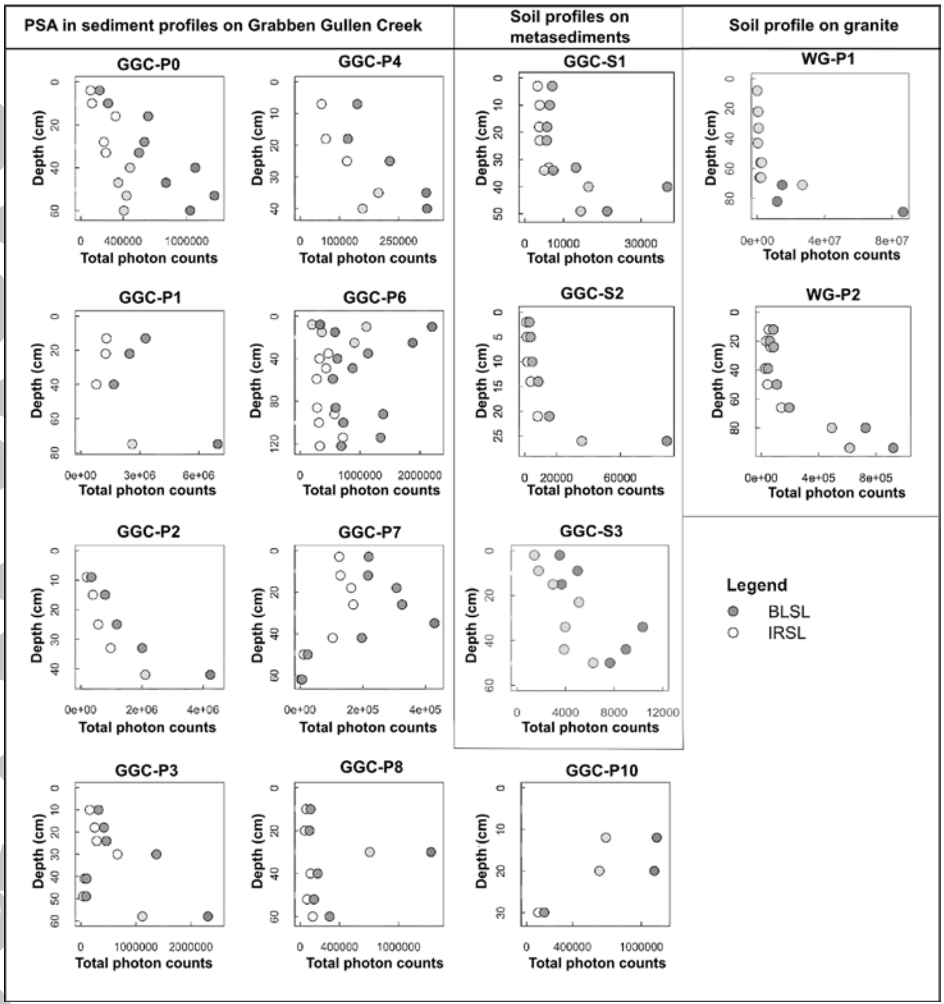

Figure 8. Plot of maximum luminescence signal for all portable luminescence reader profiles in the PSA and soil profiles sampled in the Grabben Gullen Creek catchment.

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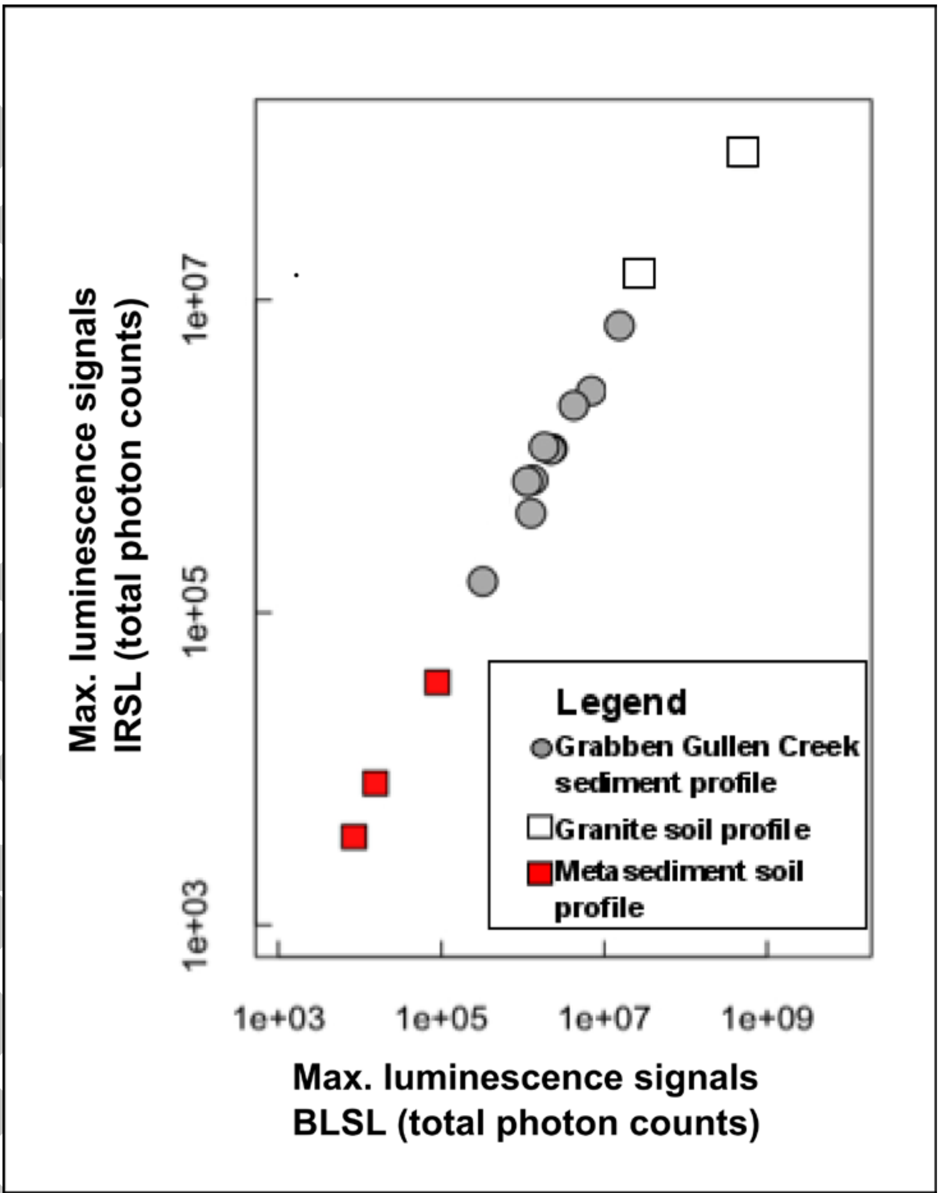

Figure 9. Luminescence signals measured in (left) the profiles through PSA in Grabben Gullen Creek, and profiles in soils formed on metasediments (middle), and granite (right). Note that the maximum portable reader signals in the PSA profiles occur at different depths, but always in the deeper parts of soil profiles.

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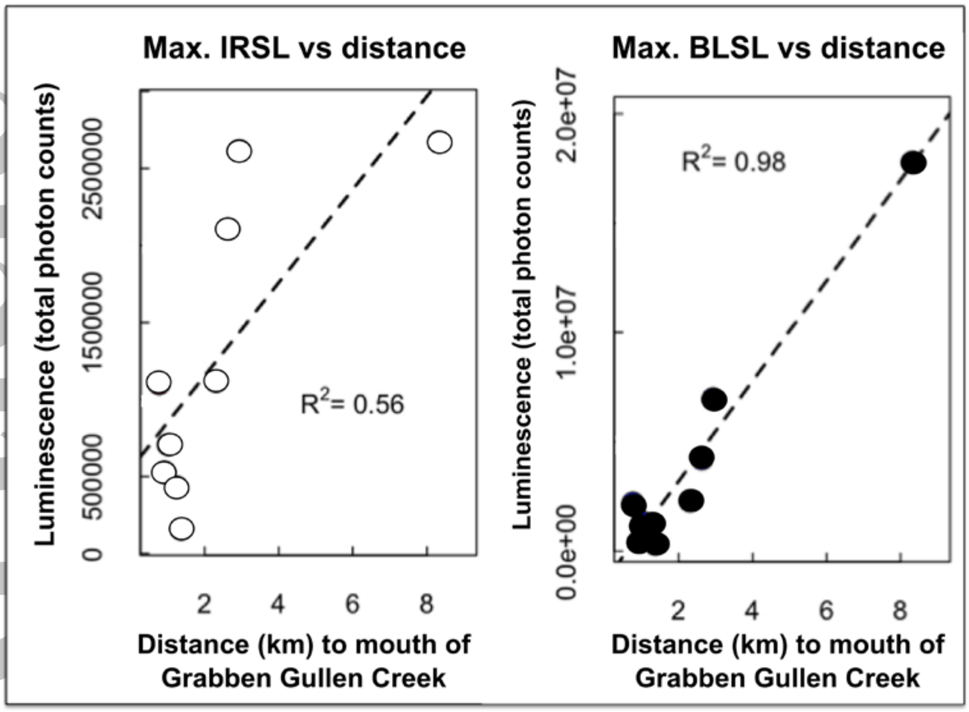

Figure 10. Plots of maximum luminescence signals in the PSA profiles on Grabben Gullen Creek plotted against distance upstream from the confluence of Grabben Gullen Creek and the Lachlan River. BLSL and IRSL maximum signals decrease downstream.

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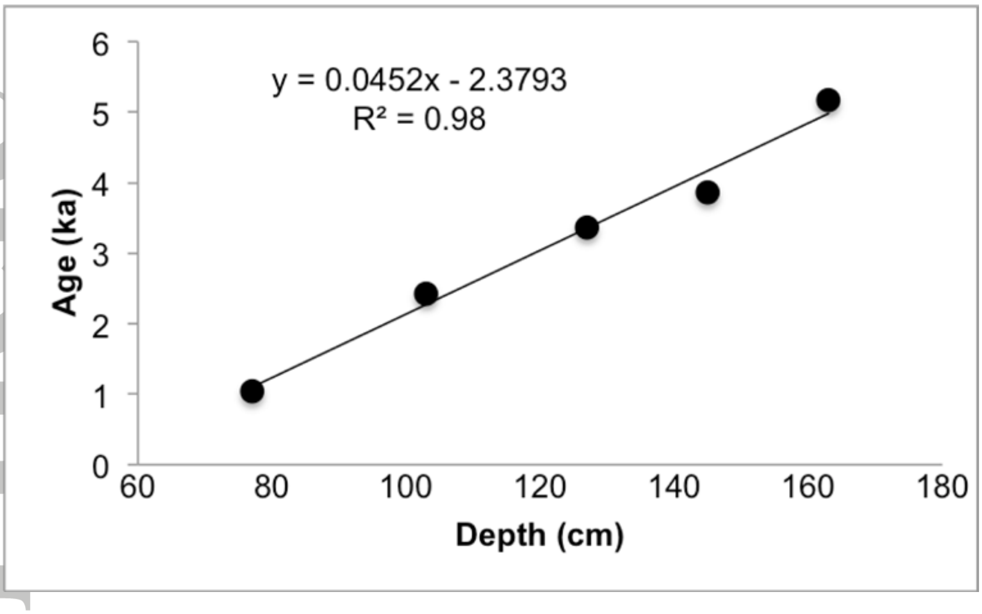

Figure 11. Age-depth plot of OSL ages in the upper metre of the SM, with linear regression model using the five age determination shown in Table 1. The equation yields an age of 378 a for the SM-PSA contact at 61 cm depth.

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