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Landscape preservation under post-European settlement alluvium in the south-eastern Australian tablelands, inferred from portable OSL reader data

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ABSTRACT: Human land-use changes leading to widespread erosion and gully incision have been well studied, but the effects that erosion and sediment mixing, which accompany the deposition of post-(European) settlement alluvium (PSA), have in valley bottoms and wetlands receive considerably less attention. PSA overlying pre-disturbance swampy meadow (SM) wetland sediments is commonly exposed along incised stream channel gully walls throughout the south-eastern Australian Tablelands, providing an ideal setting in which to assess and understand better how PSA deposition affects valley bottoms and the wetland environments that often occupy them. Portable optically stimulated luminescence (pOSL) reader data were measured on bulk sediment samples from SM-PSA stratigraphies at 16 locations throughout the south-eastern Australian Tablelands to assess the effects of erosion and sediment mixing at the SM-PSA boundary. Trends of pOSL data with depth at each profile were used in conjunction with visual profile descriptions to identify the stratigraphic boundary between SM and PSA sediment and to infer the degree of valley bottom erosion and sediment mixing during PSA deposition. At most sites, SM sediments experienced minimal, if any, disturbance during PSA deposition, and we refer to these as non-eroded sites. Many sites, however, experienced a significant degree of erosion and sediment mixing – eroded sites – often corresponding to visually diffuse sedimentary boundaries between the two stratigraphic units. Our findings demonstrate that SM landscapes in the Tablelands can be preserved with minimal disturbance under PSA at non-eroded sites and are preserved beneath a mixing zone at all eroded sites. Copyright © 2016 John Wiley & Sons, Ltd.

KEYWORDS: optically stimulated luminescence; portable OSL reader; Australia; PSA; preserved landscapes

Introduction

Soil erosion caused by sudden deforestation, vegetation degradation, and concomitant aggradation of the eroded sediment on lower slopes, valley bottoms, wetlands, and estuaries are amongst the most problematic of geomorphological processes in the Holocene (e.g. Valette-Silver *et al.*, 1986; Dugmore *et al.*, 2000; Toy *et al.*, 2002; Nyssen *et al.*, 2004; Knox, 2006; Wilkinson and McElroy, 2007; Beach *et al.*, 2009; Richardson *et al.*, 2014). Such deforestation is commonly associated with the first arrival of human populations, or in many cases, the secondary arrival of colonists, European or otherwise. Thus, aggradational deposits resulting from erosion in headwater catchments are commonly referred to as post-settlement alluvium (Starr, 1989), or post-European settlement alluvium (PSA) when specifically referring to erosion resulting from land-use change following European colonization (Portenga *et al.*, 2016).

Recent research has focused on the upstream erosion that led to PSA deposition because the scars left by erosion on landscapes form quickly, are vast in scale, recover slowly, and are difficult to predict, often becoming permanent features of the landscape (e.g. Eyles, 1977b; Poesen *et al.*, 2002; Stankoviansky, 2003; Reusser and Bierman, 2010; Hooke *et al.*, 2012). Although PSA deposition is directly related to upstream erosion and is globally widespread (e.g. Machado *et al.*, 1998; Dugmore et al., 2000; Lang *et al.*, 2003; Lespez, 2003; Fuchs *et al.*, 2004; Nyssen *et al.*, 2004; Dugmore et al., 2005; Beach et al., 2006; Sandgren and Fredskild, 2008; Beach et al., 2009; Coltorti *et al.*, 2010; Damm and Hagedorn, 2010; Kidder *et al.*, 2012; Massa *et al.*, 2012; Richardson *et al.*, 2013), it receives less research attention, perhaps because PSA deposits can go unnoticed in a landscape once vegetation becomes established on the sediment (Walter and Merritts, 2008; Merritts *et al.*, 2011). As a result, we know comparatively little about the geomorphological processes – erosion, sediment mixing – operating on valley bottoms during PSA deposition.

Most of what is known about PSA and its deposition comes from two geographical regions: the upper mid-western and eastern United States and south-eastern Australia. In the United States, PSA deposition in headwater tributaries of the Mississippi River catchment occurred in the early- to mid-AD 1800s after non-native Americans felled forests for agricultural and mining purposes (Knox, 1977; Trimble, 1983; Magilligan, 1985). PSA deposition was rapid and widespread throughout the Mississippi River catchment, leading to floodplain aggradation and burial of important Native American cultural and archaeological sites (Bettis and Hajic, 1995; Bettis and Mandel, 2002; Stafford and Creasman, 2002; Arco *et al.*, 2006; Knox, 2006). Further east, non-native American deforestation along the mid-Atlantic coast resulted in increased erosion and sedimentation in Chesapeake Bay (Valette-Silver *et al.*, 1986; Helz and Valette-Silver, 1992; Cooper and Brush, 1993). PSA also back-filled mill dams and was re-vegetated so completely after the dams were abandoned that the PSA was presumed to be part of an undisturbed natural landscape (Walter and Merritts, 2008; Merritts *et al.*, 2011); actual pre-disturbance landscapes, however, have been identified after PSA was removed (Booth *et al.*, 2009; Hartranft *et al.*, 2011; Merritts *et al.*, 2011).

South-eastern Australia shares a similar history. European deforestation and grazing livestock were introduced to eastern New South Wales in the early AD 1800s, which further degraded vegetation cover already stressed by drought (e.g. Rustomji and Pietsch, 2007; Portenga *et al.*, 2016). These conditions rendered the landscape exceptionally prone to regional gully erosion, and thus PSA deposition for the following ~130 years (Eyles, 1977b; Prosser, 1991; Wasson *et al.*, 1998; Scott, 2001; Rustomji and Pietsch, 2007; Portenga *et al.*, 2016). The immediacy with which PSA deposition followed European arrival to the region, and its continuation through historically wet periods, sets PSA deposition apart from pre-European cut-and-fill cycles that were frequent in south-eastern Australia during arid periods of the Holocene only (Prosser, 1991; Prosser and Winchester, 1996; Brierley and Mum, 1997; Brierley and Fryirs, 1998; Brierley and Fryirs, 1999; Ericksson *et al.*, 2006; Johnston and Brierley, 2006; Cohen and Nanson, 2007; Rustomji and Pietsch, 2007; Portenga *et al.*, 2016). Pre-disturbance valley bottom sediment and European and Aboriginal artefacts and archaeological sites are often reported being incorporated into or buried under PSA deposits (Starr, 1989; Feary, 1996; Holdaway *et al.*, 1998; Wasson *et al.*, 1998; Fanning, 1999; Gore *et al.*, 2000), illustrating the idea that valley bottom landscapes in the south-eastern Australia are reworked and eroded during PSA transport and deposition. To what degree pre-disturbance landscapes were reworked by and during PSA transport and deposition remains uncertain and is the focus of the remainder of this paper.

In this study, we assess how valley bottom landscapes were reshaped by the erosion and sediment mixing processes that accompany PSA deposition. Our study focuses on the south-eastern Australian Tablelands (Figure 1) where discontinuous gullies incised into headwater catchments following European deforestation and land-use change; eroded sediment was deposited downstream from the mouth of each gully as thick (>10 cm), sandy PSA (Figure 1) (e.g. Eyles, 1977a; Erskine and Melville, 1983; Prosser and Slade, 1994; Prosser and Winchester, 1996; Wasson *et al.*, 1998). Eventually, discontinuous gullies lengthened and merged by headward stream incision, incising through PSA deposits and the underlying dark, clay-rich swampy meadow (SM) wetland sediments of the pre-disturbance landscape (Figure 2) (Mactaggart *et al.*, 2008; Muñoz-Salinas *et al.*, 2014; Portenga and Bishop, 2016). Although some swampy meadows still exist (i.e. not buried by PSA – e.g. Prosser, 1991; Prosser and Slade, 1994; Portenga and Bishop, 2016), such incision now exposes a near-ubiquitous stratigraphy of PSA overlying SM sediment in vertical gully walls throughout the Tablelands (Figure 1). We assess specifically the degree of disruption to characteristic depth profiles of bulk sediment optically stimulated luminescence (OSL) in SM sediment by PSA deposition in disturbed Tablelands catchments (Portenga and Bishop, 2016).

Methods

Our assessment of valley bottom landscape disturbance is guided by the analysis of OSL measurements made using a portable OSL (pOSL) reader on bulk sediment collected in vertical profiles through SM-PSA stratigraphic exposures in gully walls. OSL signals accumulate over time in buried mineral grains in response to natural irradiation of the grains by radioactive minerals in the surrounding sediment. OSL is stored in the mineral grains until they are eroded, exposed to, and stimulated by sunlight, at which point the stored luminescence signal is emitted through a process called bleaching (Aitken, 1998). Typically, bleaching occurs quickly when sediment is exposed to sunlight (Godfrey-Smith *et al.*, 1988); however, turbidity and the dimming of light passing through water lessen the bleaching efficiency (Ditlefsen, 1992; Rendell *et al.*, 1994; Jain *et al.*, 2004; Rhodes, 2011). For these reasons, sediment transported through fluvial systems is often incompletely bleached and deposited with an inherited luminescence signal (Wallinga, 2002; Thomas *et al.*, 2006; Rittenour, 2008). The measurement of this inherited luminescence using pOSL readers has been used to understand geomorphological processes in coastal, aeolian, fluvial, glacial, and archaeological settings (Bishop *et al.*, 2005, 2011; Sanderson and Murphy, 2010; Muñoz-Salinas *et al.*, 2011, 2012, 2013, 2014; Kinnaird *et al.*, 2012, 2013; Munyikwa *et al.*, 2012; Stang *et al.*, 2012; Castillo *et al.*, 2014; King *et al.*, 2014; Munyikwa and Brown, 2014; Bateman *et al.*, 2015; Stone *et al.*, 2015; Palamakumbura *et al.*, 2016; Portenga and Bishop, 2016; Portenga *et al.*, 2016).

Sediment transport through the SM wetlands that were prevalent in Tablelands valley bottoms before European arrival was by slow, shallow, low-energy flows that ensured that there was sufficient sediment exposure to sunlight to bleach any inherited OSL before the sediment was reburied (Eyles, 1977b; Prosser and Winchester, 1996; Scott, 2001). As a result, bulk sediment OSL measurements through SM sediment exhibit a characteristic luminescence depth profile with zero or minimal OSL at the surface and a systematic increase of OSL with increasing depth, related to the SM sediment burial age (Muñoz-Salinas *et al.*, 2014; Portenga and Bishop, 2016). PSA derived by gully erosion during storms, however, was transported and deposited by floods under poor bleaching conditions; as a result, the bulk sediment OSL of PSA retains inherited luminescence, equivalent to the luminescence of its source material, many times greater than that of the relatively well-bleached SM sediments that it buries (Muñoz-Salinas *et al.*, 2014). The transition from SM depositional conditions to PSA depositional conditions is reflected in the SM-PSA bulk sediment OSL profiles by a change from pOSL data that decreases with decreasing depth through SM sediment to the base of the PSA deposit where pOSL data increases significantly (Muñoz-Salinas *et al.*, 2014; Portenga and Bishop, 2016). Interactions between the PSA, as it is being transported and deposited, and SM valley bottom sediment may therefore also be revealed by analysis of bulk sediment OSL depth profiles.

We collected sediment samples at 3 cm intervals at 16 SM-PSA profiles exposed in catchments of various sizes and lithologies throughout the south-eastern Australian Tablelands (Figure 1, Table I), with two of the 16 profiles being collected along Birchams Creek. We were unable to map the extent of PSA deposition at these sites but PSA is often visible on both banks of the creeks along tens of metres of gully wall

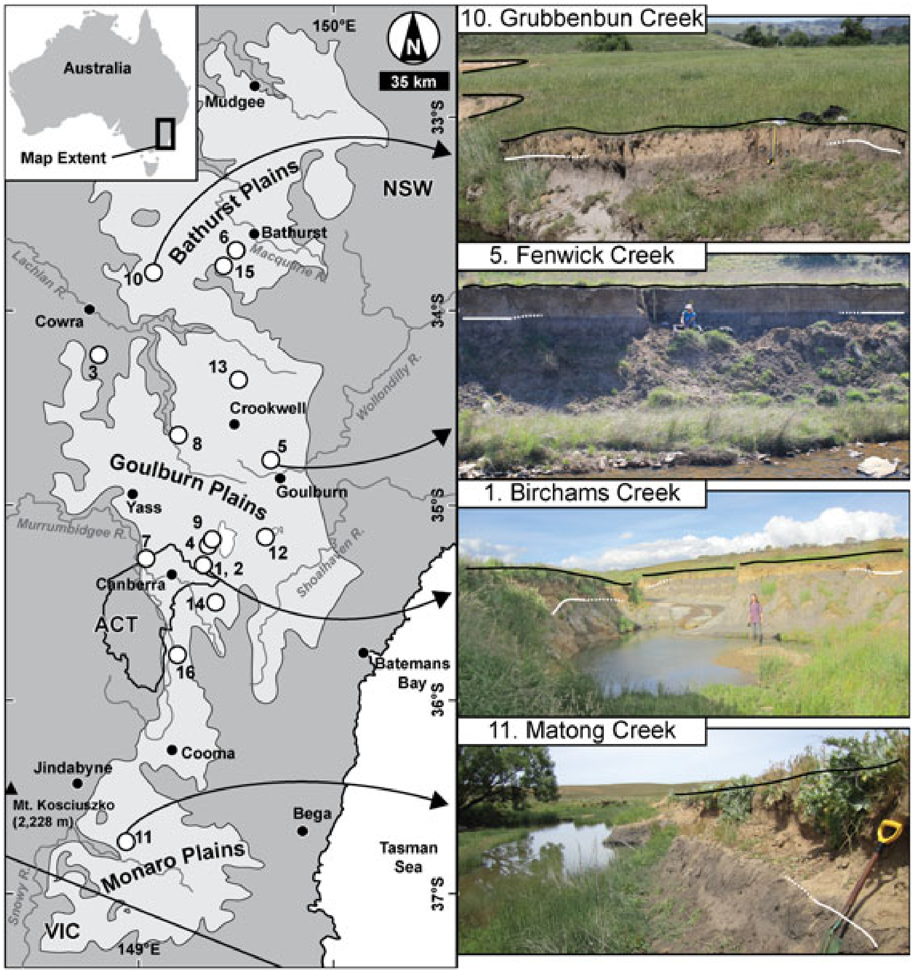

Figure 1. Location of the south-eastern Australian Tablelands (inset and light grey shaded area) and the field sites mentioned in this study (white circles): 1 and 2: Birchams Creek; 3: Breakfast Creek; 4: tributary to Brooks Creek; 5: Fenwick Creek; 6: Georges Plains Creek; 7: Gooromon Ponds Creek; 8: Grabben Gullen Creek; 9: Groves Creek; 10: Grubbenbun Creek; 11: Matong Creek; 12: Mulwaree River; 13: Phils River; 14: Primrose Valley Creek; 15: Queen Charlotte's Creek; 16: Ryries Creek. Cities and towns (black circles) in New South Wales (NSW) and the Australian Capital Territory (ACT) are given for geospatial reference; the state of Victoria (VIC) is shown at the bottom of the map. Arrows point to respective photographs of SM-PSA stratigraphies exposed in gully walls throughout the south-eastern Australian Tablelands. Birchams Creek, ~4 m high exposure from present creek bed to top of gully wall. Fenwick Creek, ~3 m exposure. Grubbenbun Creek, ~1.5 m exposure. Matong Creek, ~2 m exposure. In the photographs, solid black lines trace the upper limit of PSA, which makes up the modern valley bottom surface; dashed white lines indicate the transition from SM sediments to PSA, only tracing a portion of the exposure for visibility.

exposures, and we presume that PSA is deposited laterally across the valley bottoms at our sites, as has been documented elsewhere in the Tablelands (e.g. Prosser and Winchester, 1996; Wasson *et al.*, 1998; Rustomji and Pietsch, 2007). Samples were collected using 18 mm diameter × 30 mm length light-proof aluminium tubes, capped at each end with multiple layers of thick tape, and measured in dark-rooms set up in the field. In collecting these samples, we build on our previous study that demonstrates the reproducibility of pOSL reader data (Portenga and Bishop, 2016) to address a secondary aim in this study, namely, testing the sensitivity of pOSL reader data to sample placement in a sediment exposure. Thus, at two sites, Fenwick Creek and Mulwaree River, we collect secondary sediment profiles, at 9 cm depth intervals ~10 to 15 cm laterally away from the main profile. We plot the resulting data with depth to gauge how our interpretations of valley-bottom disturbance determined from the main profile might change had we collected samples for our main profile from 10 to 15 cm to the left or right along the gully wall.

Samples from four sites were analysed for bulk sediment mineralogy and grain size to assess whether down-profile changes in bulk OSL are affected by changes in bulk sediment mineralogy or grain size distributions (Sanderson and Murphy, 2010; Munyikwa and Brown, 2014; Bateman *et al.*, 2015). We also assessed whether down-profile changes in bulk sediment OSL data might be the result of down-profile changes in sediment dose rates.

Bulk sediment OSL for each sample was measured using a Scottish Universities Environmental Research Centre pOSL reader (Sanderson and Murphy, 2010). Samples were not exposed to any type of heat source during pOSL reader measurement, neither were samples irradiated or tested for sensitivity at any point during the measurement process. Each sample was first exposed to 60 seconds of infrared (IR) stimulation, and the uncorrected infrared stimulated luminescence ($IRSL_u$) emitted from each sample during this stage was measured; subsequently, each sample was exposed to 60 seconds of blue-light (BL) stimulation, and the uncorrected blue-light stimulated luminescence ($BLSL_u$) emitted from each sample was measured. Dark counts – luminescence detected in the absence of stimulation – were measured for 15 seconds before the IR stimulation cycle (DC1), between the IR and BL stimulation cycles (DC2), and after the BL stimulation cycle (DC3). DC1 and DC2 were doubled and subtracted from the $IRSL_u$ measurement, thus providing the net IRSL measurement:

$$IRSL = IRSL_u\text{-}(2 \times DC1)\text{-}(2 \times DC2) \quad (1)$$

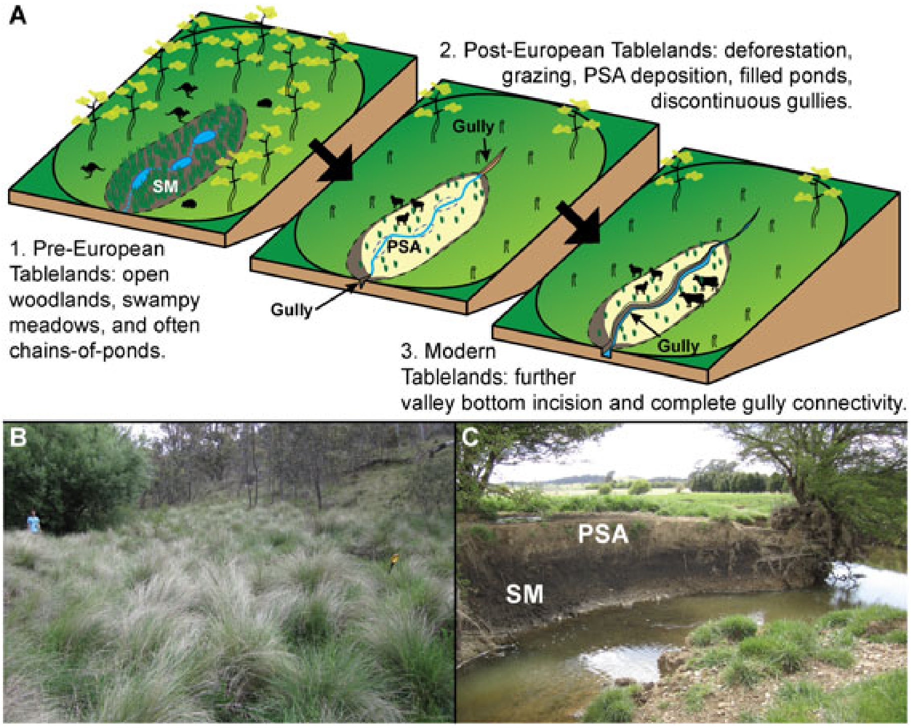

Figure 2. From Portenga *et al*., 2016. (A) Schematic representation of landscape change in the south-eastern Australian Tablelands from a typical pre-disturbance catchment environment (left) to a post-disturbance, incised catchment (right). (B) Photograph of modern swampy meadow at Wangrah Creek (Portenga and Bishop, 2016); person for scale. (C) Photograph of SM-PSA stratigraphy at Primrose Valley Creek (Figure 1).

Similarly, DC2 and DC3 were doubled and subtracted from the $BLSL_u$ measurement, thus providing the net BLSL measurement:

$$BLSL = BLSL_u\text{-}(2\times DC2)\text{-}(2\times DC3) \tag{2}$$

All pOSL measurements are given in units of photon counts.

Results

Each of the profiles we sampled exhibited discernible SM and PSA units, with varying degrees of sedimentological gradation between the two units (Figure 3). No relationships between bulk sediment OSL and mineralogy or grain size were observed (see Supplementary Information), and dose rates measured on multiple SM-PSA profiles throughout the Tablelands show no discernible down-profile trends within the measurement uncertainties (Rustomji *et al*., 2006; Portenga *et al*., 2016). At most profile sites, bulk sediment OSL data from SM sediment have near-zero luminescence at the SM-PSA transition and increase with increasing depth through the profiles (Figure 3). Replicate SM samples from Fenwick Creek return small ranges of bulk sediment IRSL and BLSL (Figure 4). PSA replicates return larger ranges of bulk sediment IRSL and BLSL that are significantly greater than IRSL and BLSL in the uppermost SM sediment; even at PSA depths at Fenwick Creek where the range of replicate luminescence data is small (e.g. 66 cm), the IRSL and BLSL values are all much greater than in SM sediment. Bulk IRSL and BLSL from PSA and from SM replicate samples at Mulwaree River all exhibit large data ranges, and the pOSL measurements from SM sediments do not exhibit the increase of bulk sediment OSL with increasing depth through the profile that is observed at most other sites (Figure 4).

Sedimentological boundaries between SM and PSA are clearest at Birchams 1, Fenwick, Georges Plains, Gooromon Ponds, Grabben Gullen, Groves, Matong, and Ryries Creeks and Phils River (Figure 3). Bulk sediment OSL maxima in these profiles tend to occur in PSA immediately above the SM-PSA transition, though a gradual increase to the bulk OSL maxima in PSA is seen at Birchams 1 Creek and Georges Plains Creek. Bulk sediment OSL in the uppermost SM sediment at these creeks is nearly zero, relative to bulk sediment OSL maximum values in the PSA, and bulk sediment OSL increases with increasing depth below the SM-PSA boundary at these sites.

Bulk sediment OSL profiles at Birchams 2, Breakfast, Brooks, Grubbenbun, and Queen Charlotte's Creeks all exhibit gradual visual boundaries between SM sediment and the overlying PSA (Figure 3). These transitions are associated with bulk sediment OSL depth-profiles that do not reach near-zero luminescence in the SM sediment. The inflection point of these profiles, demarcating the transition from SM to PSA sediment, has bulk sediment OSL much greater than zero, and the bulk sediment OSL in SM sediment decreases with decreasing depth to the SM-PSA transition and then gradually increases to bulk OSL maxima in the PSA.

The SM sediment and PSA at Breakfast and Primrose Valley Creeks and Mulwaree River appear to be visually distinct (Figure 3); however, the bulk sediment OSL depth-profiles are chaotic throughout. Although bulk sediment OSL through what visually appears to be PSA at these sites resembles the OSL profiles through PSA at other sites, bulk sediment OSL profiles in what appears to be SM sediment do not resemble characteristic SM depth-trends.

Discussion

We interpret the pOSL data presented in this study to reflect the effectiveness of bleaching conditions during sediment deposition based on the observed lack of relationship between pOSL reader data and mineralogy, grain size, and sediment dose rates in the Tablelands (see Supplementary Information) (Rustomji

Table I. Sample site descriptions.

Figure 1 label	Sample site	Latitude (°S)	Longitude (°E)	Upstream catchment area (km^2)	Upstream lithologies	Sample use (n =)				Degree of SM disturbance
						Bulk OSL	Grain size	XRD	Sample replicate	
1	Birchams Creek 1	35.2329	149.3139	3.7	Sandstone	38				Non-eroded
2	Birchams Creek 2	35.2291	149.3156	3.2	Sandstone	30				Eroded
3	Breakfast Creek	34.1032	148.7437	69.7	Tuff	20				Eroded
4	Brooks Creek (inset bar)	35.1141	149.3464	81.1	Undifferentiated Granite	29				Eroded
5	Fenwick Creek	34.6703	149.6768	21.0	Sandstone Basalt Granite Mudstone Siltstone	31	10	10	X	Non-eroded
6	Georges Plains Creek	33.5239	149.4886	51.9	Granite	20				Non-eroded
7	Gooromon Ponds Creek	35.1981	149.0071	81.7	Mixed metamorphic Mudstone	32				Non-eroded
8	Grabben Gullen Creek	34.5362	149.1752	175.1	Tuff Basalt Granite	120	10	10		Non-eroded
9	Groves Creek	35.0912	149.3533	5.6	Mixed sedimentary Sandstone	24				Non-eroded
10	Grubbenbun Creek	33.6503	149.0425	66.9	Granite	20				Eroded
11	Matong Creek	36.7383	148.8906	172.3	Mixed sedimentary Granite	37				Non-eroded
12	Mulwaree River	35.0827	149.6483	74.3	Mixed sedimentary Mixed sedimentary	30	10	10	X	Complex
13	Phils River	34.2397	149.5026	67.1	Tuff Basalt Granite Ignimbrite	28				Non-eroded
14	Primrose Valley Creek	35.4403	149.3781	60.3	Mixed sedimentary Mudstone Sandstone Schist	30	10	10		Complex
15	Queen Charlotte's Creek	33.6092	149.4222	4.2	Granite	20				Eroded
16	Ryries Creek	35.7195	149.1699	69.1	Undifferentiated Granite Ignimbrite Sandstone	30				Non-eroded

Note: OSL, optically stimulated luminescence; XRD, X-ray diffraction; SM, swampy meadow.

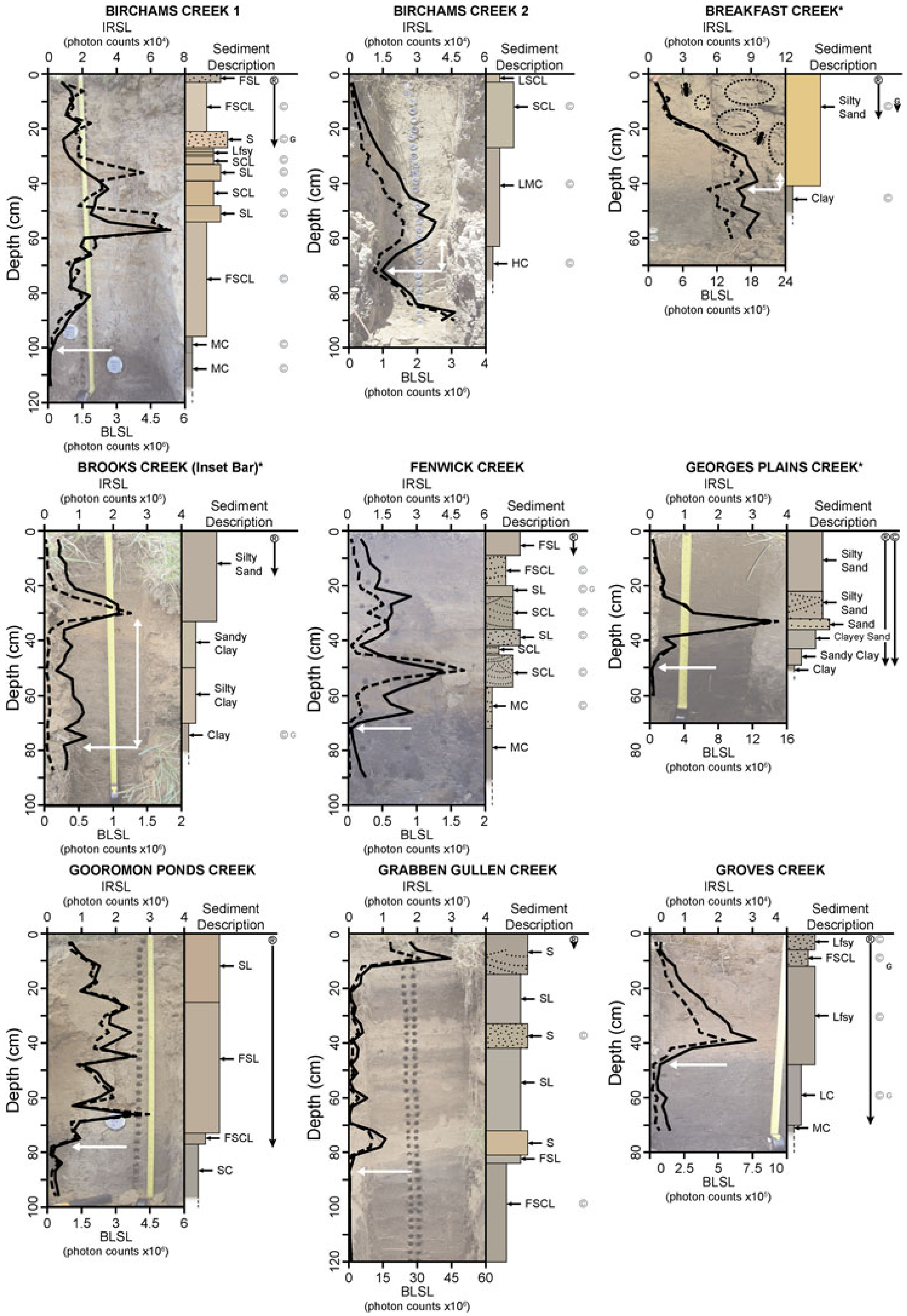

Figure 3. Field photographs and bulk sediment IRSL and BLSL data (dashed and solid black lines, respectively). Solid white arrow shows SM-PSA transition depth at all profiles and solid vertical doubleheaded white arrows show the inferred mixing zone of SM sediment and PSA at eroded profiles. Dotted ellipses at Breakfast Creek highlight significant ant burrowing activity. Mulwaree River and Primrose Valley Creek show visually clear SM and PSA units, but uncharacteristic bulk sediment OSL profiles. Bulk sediment OSL below the visual SM-PSA transitions at Mulwaree River and Primrose Valley Creek (upper question mark) do not resemble data from other SM environments (Portenga and Bishop, 2016). Lower question mark at Mulwaree River is where Rustomji and Pietsch (2007) place the SM-PSA transition. Bulk sediment OSL data below the lower question mark at Primrose Valley Creek better resembles data expected of SM sediments. Full sediment profile descriptions were carried out for most profiles, except those marked with an asterisk (*), where only general sediment descriptions could be made based on visual inspection of the profile in the field.

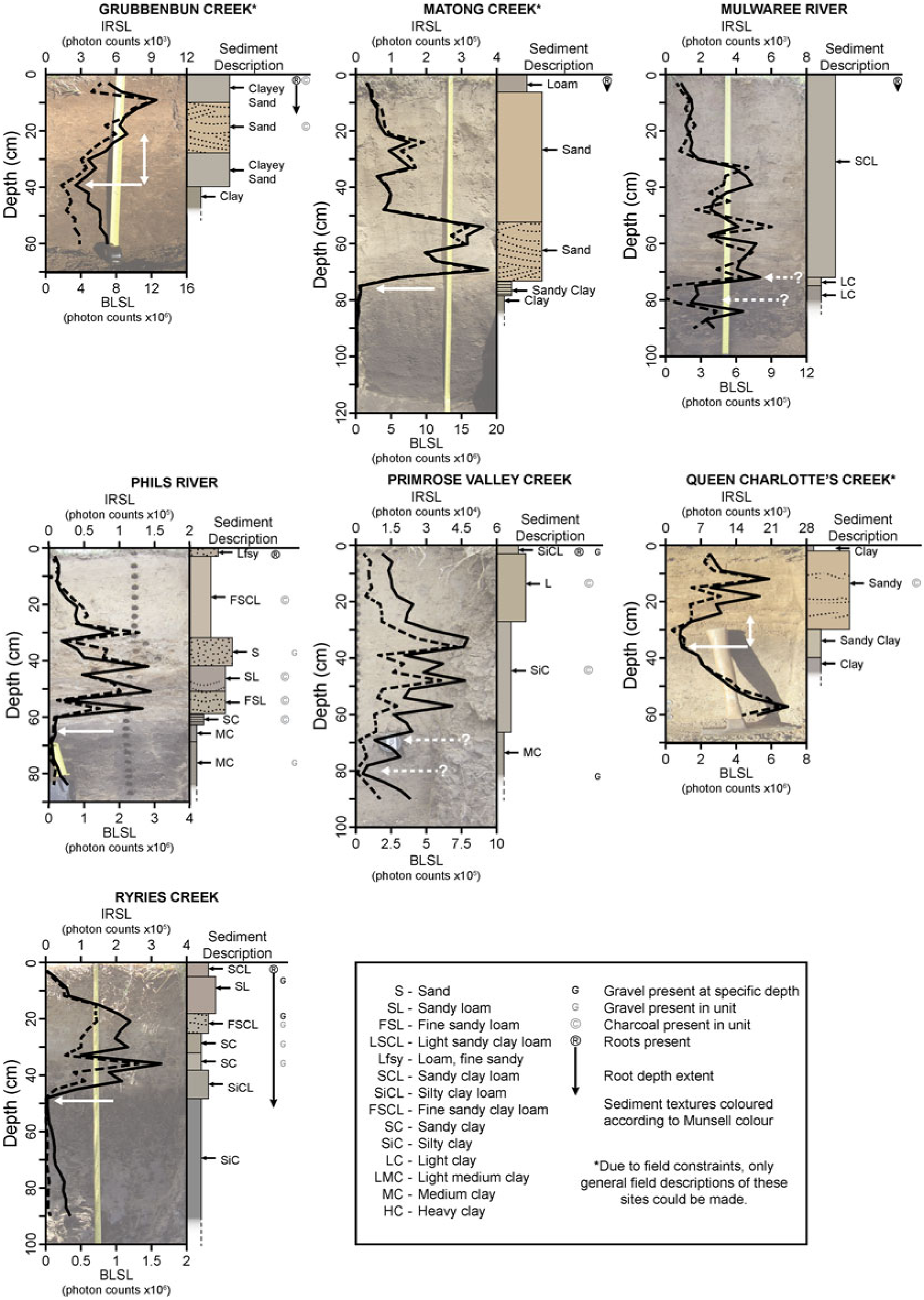

Figure 3. (Continued)

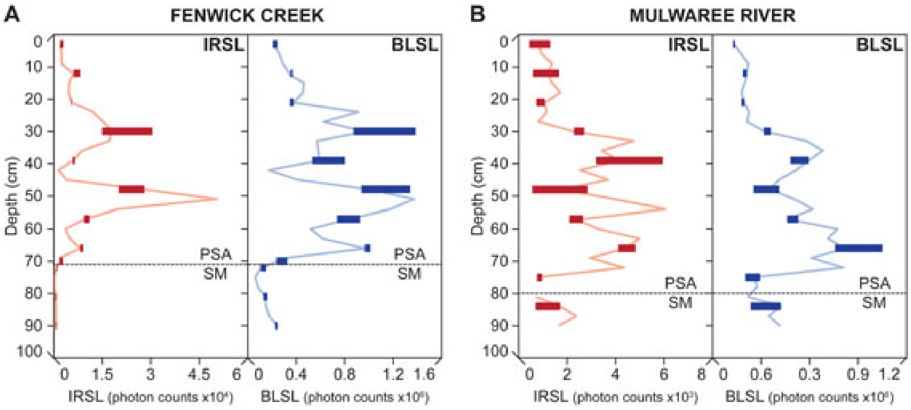

Figure 4. The range of bulk sediment IRSL and BLSL data from sample replicates at (A) Fenwick Creek and (B) Mulwaree River are shown by dark horizontal rectangles in the left and right panels of each figure, respectively. Light solid lines represent the bulk IRSL and BLSL data from the main profile at each site.

and Pietsch, 2007; Portenga *et al.*, 2016). Depth-trends of pOSL data through SM sediment at most sites closely resemble the characteristic downwardly-increasing depth trends of pOSL data from modern SM settings (Portenga and Bishop, 2016). Only a small proportion of the measured bulk sediment OSL in PSA sediment is likely to be the result of post-burial accumulation given the young age of PSA deposits in the Tablelands (e.g. Rustomji and Pietsch, 2007; Portenga *et al.*, 2016). Therefore, we agree with Muñoz-Salinas *et al.*'s (2014) suggestion that the generally abrupt increase to maximum bulk OSL measurements in the basal PSA deposits, above the SM-PSA transitions, likely reflects alluvial deposition under either gradually or rapidly diminishing effective bleaching conditions if increases to bulk OSL maxima in the PSA are gradual or sudden, respectively. We suggest the possibility that down-profile changes in bulk sediment OSL reflect changes in PSA source material is unlikely because a large proportion of the catchment area upstream from each sampling site is underlain by one dominant lithology. We do, however, approach pOSL data at Breakfast Creek with caution because an active ant colony was observed here (Figure 3), which has likely disturbed the initial post-depositional PSA depth profile to some degree (Rink *et al.*, 2013); significant bioturbation was not observed at any other site.

Bulk sediment OSL measurements decrease with decreasing depth through SM sediment to near-zero luminescence at the visible SM-PSA transition at nearly all sites (Figure 3). From this observation, we infer that the bulk OSL depth profiles through SM sediment at Birchams 1, Fenwick, Georges Plains, Gooromon Ponds, Grabben Gullen, Groves, Matong, and Ryries Creeks and Phils River have not been reworked substantially during PSA deposition. We therefore interpret the bulk OSL profiles at these sites to be indicative of minimal valley bottom disturbance during PSA deposition. We refer to these profiles as non-eroded profiles and suggest that PSA deposition, at least in the immediate environs of these profiles, did not significantly disrupt or rework pre-disturbance valley bottom landforms. This interpretation is supported by previous findings, which show that single-grain quartz OSL ages for SM sediment and PSA at Birchams 1, Gooromon Ponds, and Ryries Creeks overlap within 1σ uncertainties, suggesting there was no erosion of SM sediments during PSA deposition (Portenga *et al.*, 2016). Single-grain quartz OSL ages for SM sediment and PSA at Fenwick and Groves Creeks and Phils River show an 11 to 145 years age gap between 1σ uncertainties (Portenga *et al.*, 2016), which we suggest is either reflective of the slow sediment accumulation rate in SM wetlands (Rustomji and Pietsch, 2007; Muñoz-Salinas *et al.*, 2014) or perhaps some limited or minimal erosion of SM sediment during PSA deposition. We apply this interpretation to all non-eroded profiles (Figure 3) and suggest that SM environments and landforms are preserved, fully intact beneath PSA deposits in these catchments.

Bulk OSL depth profiles at Birchams 2, Breakfast, Brooks, Grubbenbun and Queen Charlotte's Creeks display characteristic bulk OSL profiles in SM sediment, but luminescence of SM profiles at these sites does not decrease to near-zero luminescence at the SM-PSA transition (Figure 3). We infer from this observation that substantial SM erosion and intermixing with PSA occurred during PSA deposition, and we therefore refer to these sites as eroded profiles. Visual inspections of eroded profiles in the field show clear SM and PSA sedimentary units, but with wide diffuse boundaries between them that correspond to bulk OSL in SM sediment grading upward into PSA sediment with inherited luminescence. Thus, we suggest that the SM landscapes at eroded sites have been disturbed during PSA deposition and are similar in their degree of SM disturbance to PSA deposition at Jerrabomberra Creek, near Canberra, where SM sediment was found entrained within and mixed into PSA deposits (Wasson *et al.*, 1998). Below the mixing zone at eroded sites, however, luminescence of SM sediment increases systematically with increasing depth, reflective of the characteristic SM luminescence profile we expect to find. We thus infer that PSA deposition only disturbed the uppermost portions of SM environments at these sites and suggest that SM sediments, unaffected by PSA deposition, are still preserved beneath the mixing zone.

Profiles at Breakfast and Primrose Valley Creeks and Mulwaree River appear to exhibit distinct visual SM and PSA stratigraphic units in the field, but they reveal uncharacteristic bulk OSL profiles with depth across the SM-PSA transition. Rustomji and Pietsch (2007) identified the SM-PSA transition at their WP5 Mulwaree River site – adjacent to our Mulwaree River site – at 80 cm depth, which is below the visible transition between the two units at 72 cm (Figure 3). The depth of SM-PSA transitions at most other sites was clearly identifiable using pOSL reader data, but bulk sediment OSL data at Mulwaree River, from what visually appears to be dark SM sediment, more closely resemble luminescence characteristic of PSA – that is the sediment returns large ranges of measured bulk sediment OSL. Moreover, bulk OSL data from sediment replicates through supposed SM samples at Mulwaree River are neither near-zero, nor do sample replicates return similar values as they do at Fenwick Creek (Figure 4). We therefore suggest that these apparent SM sediments more closely reflect PSA depositional conditions. We find similar uncertainties at Primrose Valley Creek where the visible transition between what appear to be dark SM and lighter PSA sediments is at 70 cm, but bulk OSL data at depths ≥70 cm at the site do not resemble typical SM profiles. It is possible that valley bottoms at Mulwaree River and Primrose Valley Creek were severely disrupted, eroded, mixed, and reworked during PSA deposition, but without bulk OSL data from deeper in the SM unit, this interpretation remains speculation. Whatever the reason, these examples of erratic bulk OSL depth profiles show that not all depositional sedimentary histories are easily interpreted from pOSL reader data, and, conversely, that stratigraphic divisions of vertical profiles based on visual inspection alone might not be fully reliable.

Although we only measured bulk OSL data from one SM-PSA profile in most catchments, the two profiles collected from the Birchams Creek catchment show that SM environments within the same catchment may be affected differently by PSA deposition. The Birchams 1 SM-PSA profile was collected from the lower reach of the creek where a series of ponds was identified from AD 1880 maps (Eyles, 1977a); the Birchams 2 SM-PSA profile was collected from a site upstream of the ponds mapped in AD 1880. Discontinuous gullying and PSA deposition occurred at Birchams Creek between AD 1880 and AD 1940 (Eyles, 1977a), probably between AD 1914 and AD 1932 (Portenga *et al.*, 2016). We suggest that PSA at Birchams 1 was delivered to one of the mapped ponds and settled on the bottom of the pond without eroding it; there were no ponds present at Birchams 2 where we infer sediment mixing occurred during PSA deposition. Thus, one bulk sediment OSL profile within any given catchment only provides an assessment of the degree of local valley-bottom disturbance during PSA deposition. We stress the importance of this interpretation that bulk sediment OSL data should only be used to interpret geomorphic processes in the immediate vicinity of the profile site. Further variability in the degree of valley-bottom reworking at different sites within a catchment likely reflects a combination of the intensity of land use at the time of gully incision, upstream catchment size, soil characteristics reflective of the bedrock lithology, and the severity of the climate or weather conditions under which gullies were incised or PSA was deposited. Each of these factors is important in its own right deserve further investigation.

Implications

The idea that SM sediments are buried under PSA deposits throughout the Tablelands is not new (Eyles, 1977b; Prosser, 1991; Rustomji and Pietsch, 2007; Muñoz-Salinas *et al.*, 2014; Portenga *et al.*, 2016), but our findings are the first to suggest that pre-European disturbance SM landscapes can be preserved underneath PSA deposits, sometimes very well. This conclusion has broad-reaching implications beyond geomorphological discussion and it may be of interest to scientists using biological records, such as native seed banks or pollen records buried by PSA, to reconstruct and understand pre-disturbance environmental conditions (e.g. Merritts *et al.*, 2011; Booth and Loheide, 2012; O'Donnell *et al.*, 2014, 2015). Similarly, understanding the degree of disturbance at any archaeological site is crucial for proper archaeological interpretation (Wood and Johnson, 1978; Wainright, 1994), and using pOSL reader data may be one way of producing such information quickly at field sites where artefacts are covered or preserved within PSA (Bettis and Hajic, 1995; Feary, 1996; Holdaway *et al.*, 1998; Lang and Hönscheidt, 1999; Lang *et al.*, 1999, 2003; Bettis and Mandel, 2002; Stafford and Creasman, 2002; Arco *et al.*, 2006).

Conclusions

Abundant exposures of SM-PSA stratigraphies in gully walls throughout the south-eastern Australian Tablelands provide a unique opportunity to examine the degree of disturbance of pre-settlement landscapes and environments by the deposition of PSA. Pre-disturbance SM landscapes with minimal, if any, valley bottom erosion can be well preserved under mantles of PSA and moderately preserved under a sediment mixing layer grading from SM sediment to PSA. Landscapes within the same catchment, however, can be altered to varying degrees – non-eroded at one location and eroded at another. The conclusions we draw from analysing bulk sediment OSL profiles are therefore reflective only of valley bottom disturbance in the immediate environs of the profile site, and not of the catchment as a whole. Although this study focuses on valley bottom disturbance during the deposition of PSA in Australia, the techniques we use and the way we interpret our data could just as well be applied to assess the degree of landscape disturbance by PSA deposition elsewhere.

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Conflict of Interest

We clarify that there are no conflicts of interest or relationships, financial or otherwise, that might be perceived as influencing our objectivity as authors.

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