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Research paper

Sediment mixing in aeolian sandsheets identified and quantified using single-grain optically stimulated luminescence

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ABSTRACT

Post-depositional mixing processes are extremely common and often obscure a record of deposition in dune and sand sheet deposits. We show that the upper half metre of a dune in southeastern Australia is currently being turned over through bioturbation, but that single-grain OSL dating and contextual knowledge can be used to identify and model these modern mixing processes. In the sandy deposits investigated, mixing processes were observed to be acting to a predicable depth of ~50–60 cm. This observation was used to develop a conceptual framework that can be applied to buried deposits and used to temporally constrain the evolution of the landform and quantify rates of mixing. When our mixing zone conceptual framework was combined with the MAM we show that phases of significant dune aggradation occurred at ~29.9, ~18.3, ~10.3 ka, and continued through the Holocene. We also present an approach using single-grain OSL data to estimate downward mixing rates, which show a strong depth dependency and are coherent with previously reported mixing rates. Modern downward mixing rates indicate that the upper ~50 cm (Zone 1) will be completely turned over on millennial time scales. While caution needs to be used when interpreting archaeological and OSL data from bioturbated sandy environments, our results demonstrate that contextual knowledge and single-grain OSL data can resolve mixing processes and contribute to an understanding of landscape evolution.

1. Introduction

Aeolian dunes and sandsheets are common landforms around the world and such features have the potential to inform us about how landscapes respond to changing climate and environmental conditions. The activation and de-activation of dune-building has been previously used to infer changes in the climate and surrounding environment, such as wind behaviour, precipitation, the presence or absence of vegetation, and sediment availability (Hesse et al., 2003; Hesse, 2014; Thomas and Shaw, 2002; Fitzsimmons et al., 2007; Telfer and Thomas, 2007). In addition, sandsheet and dune settings are often rich archaeological archives (e.g., Feathers et al., 2006; Hughes et al., 2014), and analyses of the surrounding soils can yield insights into how humans used the landscape in the past (Walkington, 2010). Thus, understanding depositional processes and post-depositional modification provides an important constraint when using such records for archaeological or palaeoenvironmental reconstruction. However, accurately dating and interpreting these landforms can be difficult due to their susceptibility to post-depositional mixing and turnover processes. Bioturbation by flora and fauna are processes that laterally and vertically displace objects (e.g., grains, gravels, artefacts) from one position to another (Schaetzl and Anderson, 2005), thereby obscuring a record of depositional history and complicating the relationship between buried materials (e.g., archaeological, palaeontological, ecological) with the surrounding substrate (Leigh, 1998; Balek, 2002; Peackock and Fant, 2002).

The development of optically stimulated luminescence (OSL) dating over the past three decades has allowed unprecedented insights into the evolution of dunes and sandsheets which often lack material suitable for radiocarbon dating. OSL dating is used to

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estimate the last time a grain of quartz or feldspar was exposed to sunlight and was subsequently buried. Aeolian-transported sediments are ideal for this method, as they are unlikely to suffer from a common problem of insufficient exposure of the grain to sunlight to completely remove its residual signal. OSL dating has allowed the development of Pleistocene dune building chronologies across the world (e.g., Thomas et al., 2003; Fitzsimmons et al., 2013; Hesse, 2014) and has potential to explore how soil mixing is manifested in grain movement. The OSL signal from single grains of quartz has been used to quantify soil movement and turnover rates (Heimsath et al., 2002; Wilkinson and Humphreys, 2005; Stockmann et al., 2013; Johnson et al., 2014; Kristensen et al., 2015) and identify phases of enhanced mixing processes in the past (Gliganic et al., 2015). Bateman et al. (2007a,b) used the OSL signal from single quartz grains to investigate a range of independently dated sandy archaeological deposits that have experienced post-depositional mixing to varying degrees. At one extreme, an unmixed stratified site with homogeneous OSL equivalent dose (De) distributions yielded ages that are consistent with independent age controls (Bateman et al., 2007a). By contrast, highly spread (i.e., over-dispersed) and skewed De data from a structureless sandy site indicated sub-surface movement of sand grains and the exhumation of underlying sandstone bedrock (Bateman et al., 2007a). While the later site yielded a stratigraphically coherent OSL chronology, it was inconsistent with robust independent age controls. This supports the conceptual bioturbation schema described by Bateman et al. (2003) that predicts that various pedoturbation and sedimentation rates may result in a coherent OSL-age-depth relationship. Importantly, this indicates that stratigraphic coherence is not necessarily indicative of an accurate OSL chronology. In these cases, the calculated OSL ages will reflect mixing-intensity, not deposition or sedimentation. Bateman et al. (2007b) suggest that bioturbational processes may explain large De scatter observed for structureless linear dune deposits from the Kalahari, questioning the robustness of the existing OSL framework for dune activity in the region (Thomas et al., 2003). Rink et al. (2013) empirically demonstrated that over a seven month period a colony of Florida harvester ants could build a 130 cm deep nest and move ~54,000 sand grains upward, thus significantly affecting De distributions and OSL age estimates for the site. They suggest that an OSL age derived from the grains with the lowest De values, identified using the minimum age model (MAM), yields the most accurate estimates of deposition for the sediments.

Indeed, statistical modelling and contextual information can be used to resolve finite burial ages for some mixed sediments (Rodnight et al., 2005; Duller, 2006; David et al., 2007; Jacobs et al., 2008; Araujo et al., 2008; Lombard et al., 2010; Lomax et al., 2011; Cohen et al., 2012; Bueno et al., 2013; Gliganic et al., 2014, 2015; Hanson et al., 2015) and OSL data has been used to quantify rates of soil mixing for *in situ* weathered soil profiles (Wilkinson and Humphreys, 2005; Stockman et al., 2013). When mixing is significant, however, the depositional signal can be completely obscured, impeding any attempt to estimate a depositional age (Feathers et al., 2006; Bateman et al., 2007a,b; Rhodes et al., 2010; Tribolo et al., 2010; Chazan et al., 2013; Gliganic et al., 2012). In these cases, a new approach is needed to develop a chronology for the evolution of the landform in question and to ascertain the degree and rates of soil/sediment turnover.

In this study we investigate significantly mixed dune deposits in a sandsheet complex in the lower Hunter River Valley in southeastern Australia. Despite decades of intensive ecological and archaeological consulting work associated with coal mining in the region, very little is published or known about the age and development of these sandsheet deposits which often contain buried archaeological remains (Hughes et al., 2014). Here, we describe novel approaches for estimating phases of dune aggradation and calculating downward mixing rates using a conceptual model that is supported by empirical observations of our optical data. Our approach utilises the identification of zero-dose grains mixed into deposits when they are within ~60 cm of the surface (the "mixing zone") and thus focuses on the downward movement of grains (i.e., "downward mixing"). We discuss the probable mechanics of mixing in this landscape, posit realistic downward mixing rate estimates, and discuss the chronology for the evolution of the dune in the regional context.

2. Context

2.1. Regional setting

Dunes and sandsheets cover approximately one third of the Australian continental land surface (Wasson et al., 1988). While linear dunes comprise the bulk of Australian desert dune fields, dunes and sandsheets are also present in the more temperate regions of eastern New South Wales such as the Blue Mountains and the Hunter valley (Story et al., 1963; Hesse et al., 2003). Dune building is not a process that is currently active in non-coastal vegetated locations in temperate southeastern Australia where relict (now vegetated) aeolian features are found. Hesse et al. (2003) showed that aeolian dunes in the Blue Mountains, New South Wales (NSW) formed during the Last Glacial Maximum (LGM) and are composed of locally derived sand from reworked soils formed from the underlying Triassic sandstone bedrock. They suggest that tree cover was vastly reduced during the LGM due to lower atmospheric carbon dioxide levels, modestly lower precipitation and colder temperatures that induced water stress in local vegetation. Such an interpretation of LGM conditions is supported by pollen records from Lake George (Singh and Geissler, 1985) and Barrington Tops (Sweller and Martin, 2001) which show that grasslands and herbfields dominated the vegetation of southeastern Australia during the LGM. This would suggest that conditions in the temperate regions of eastern Australia were more favourable for dune construction and sand sheet development during the Late Pleistocene in contrast to the modern climate.

Many rivers in temperate southeastern Australia that drain west of the Great Dividing Range and some that drain east display evidence of source-bordering dunes. Early work by Bowler (1967) reported extensive source bordering dune deposits formed on or adjacent to the Goulburn River system after the LGM (between 20 and 13 ka). Such evidence was further substantiated for other inland draining rivers which have extensive source-bordering dunes associated with large Quaternary palaeochannels (Page et al., 1991, 2009). Aeolian dunes adjacent to rivers but also on high elevation plateaus have been dated using thermoluminescence (TL) by Nott and Price (1991) as being Late Pleistocene in age. All such investigations on source-bordering dune deposits have invoked late Pleistocene climatic conditions suitable for downwind sand accumulation (e.g. increased seasonality and wind strength and/or reduced vegetation). However none of the existing investigations have directly assessed the potential role of bioturbation or mixing on the derived chronologies, representing a potential issue for the derived depositional ages and the associated palaeoclimatic interpretation.

The distribution, age and palaeoenvironmental significance of aeolian deposits in other temperate locations is less clear. Hughes et al. (2014) report the results of archaeological and geochronological investigations of bioturbated sand deposits nearby those discussed in this study in the Hunter River Valley in southeastern Australia. They report OSL ages derived from multi-grain aliquots and central age model analyses from single quartz grains of ~88-83