

1 **Is there evidence for global-scale forcing of southern hemisphere Quaternary desert**  
2 **dune accumulation? A quantitative method for testing hypotheses of dune system**  
3 **development**

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10  
11 **Abstract**

12 Luminescence dating of desert dune sediments has generated many hundreds of ages,  
13 many used in reconstructions of Quaternary environmental changes, others in attempts to  
14 elucidate dune processes. Environmental and climatic interpretations of these records have  
15 proved problematic and it remains challenging to test hypotheses of the systematic  
16 response of dunefields to changes in external forcing in the past and to make predictions of  
17 the future. We use a method that quantifies dune sediment accumulation to interpret dune  
18 luminescence age datasets, rather than simply using the ages themselves as proxies of  
19 change. The *Accumulation Intensity* method allows periods of dune sediment accumulation,  
20 here over the timescale  $10^2$ - $10^5$  years, to be identified from compilations of dated sand sea  
21 stratigraphic sequences. We apply this approach to two of the largest dune age datasets,  
22 from southern Africa and Australia, testing whether or not dunefield accumulation has co-  
23 varied in the Late Quaternary and whether systematic relationships to external drivers at  
24 global, hemispheric, regional and local scales can be identified.

## 26 **Keywords**

27 Luminescence dating dune accumulation Quaternary Southern hemisphere climate  
28 forcing

## 29 **Introduction**

30 More than 10% of the world's drylands are covered by aeolian sand dunes. These are  
31 mainly found in extensive 'sand seas' (*cf* McKee 1979) that are found in a range of climatic  
32 contexts today. These include dunes that are active, in arid-hyperarid regions, and those in  
33 regions where conditions are not conducive to the regular and sustained operation of  
34 aeolian processes, including in semiarid areas. Aeolian dunes, in degraded or heavily  
35 vegetated states, are also found in wet tropical (O'Connor and Thomas 1999) and  
36 temperate (e.g. Hesse et al. 2003) zones. The extent of these aeolian systems can  
37 represent significant proportions of the land surface with, for example, over 30% of tropical-  
38 subtropical Africa and almost 40% of Australia, including in the more temperate southeast,  
39 covered by dunes. Knowing how these dune systems will respond to global warming is a  
40 challenge that requires data on both the controls of aeolian activity and their susceptibility to  
41 change, and on the sensitivity and dynamics of dunefields in the past (Thomas and Wiggs  
42 2008).

43  
44 Luminescence dating (optically-stimulated: OSL, and thermoluminescence: TL dating) of  
45 dune sediments has, since the 1980s (Singhvi et al. 1982), been a key component of  
46 research that has attempted to unpack the evolutionary history of desert dunefields  
47 (Lancaster et al. 2016). As well as contributing to Quaternary palaeoenvironmental  
48 reconstructions in regions where other archives are rarely available (e.g. Thomas and  
49 Burrough 2012), these data can provide perspectives on the geomorphic evolution of dunes  
50 that exceed the temporal range of process-based investigations (e.g. Bristow et al. 2007).

51 Changes in desert dune system dynamics, and the resultant sedimentary archives, are due  
52 to a range of immediate driving factors including aspects of climate, particularly wind energy  
53 (e.g. Livingstone et al. 2007) and rainfall (e.g. Thomas et al. 2005); the presence and type  
54 of vegetation (e.g. Yan et al. 2015); sediment supply (e.g. Vermeesch et al. 2010); and  
55 topographic and pattern changes in the dune system itself (e.g. Lucas et al. 2015). These  
56 immediate drivers are themselves influenced by exogenous factors including orbital forcing  
57 (e.g. Lu et al. 2005) and oceanic influences (e.g. Li et al. 2014). The extent to which these  
58 factors drive regional, hemispheric or global dune system dynamics remains an open  
59 question.

60

61 It has long been proposed that subtropical dunefields were more active during glacial times  
62 (Sarnthein 1978), in response to globally-enhanced aridity and greater wind strengths. A  
63 counter argument is that, even if precipitation was reduced, lower glacial-age temperatures  
64 would have rendered precipitation more effective in these regions, supporting greater, not  
65 reduced, vegetation cover (Chevalier and Chase 2016). Whether dune sedimentary  
66 archives represent records of past aridity changes, or of windiness, is also debated, and  
67 therefore palaeoclimatic interpretations of dune age records have been questioned (Chase  
68 2009). For some dunefields, the limited spatial coverage within the age data set, and the  
69 limited vertical sampling through dune sediment profiles, may further hamper the  
70 palaeoclimatic interpretation of records (Bailey and Thomas 2014). We however consider  
71 the lack of a robust method for assimilating and analysing dune age records to be the  
72 primary constraint for addressing critical questions about long-term dune system behaviour  
73 and responses to changes in external drivers. The aim of this study is first to provide a  
74 quantitative method for the robust analysis of dune age records. Second, for the southern  
75 hemisphere, we then apply our *Accumulation Intensity (AI)* method to test the 'LGM dune

76 accumulation' hypothesis with data derived directly from dunefields. We then examine *AI*  
77 data against records of potential forcing factors and other regional proxies to explore  
78 whether systematic relationships at global, hemispheric, regional and local scales can be  
79 identified.

80

## 81 **Sedimentary records as archives of climate and environmental changes**

82 Recently there have been some challenges to the concept of using terrestrial sedimentary  
83 archives, resulting from the temporal dynamics of fluid processes, as records of past  
84 environmental and climate changes. For fluvial systems, critiques have included modelled  
85 studies proposing that system-internal (autogenic) drivers of sediment accumulation  
86 override the influence of external forcing factors, 'shredding' the potential capacity of  
87 accumulated records to preserve climate signals (Jerolmack and Paola 2010). For aeolian  
88 systems, Jerolmack et al. (2012) also argue that autogenic factors (in this case distance-  
89 controlled boundary layer effects) override climatic controls in explaining dunefield  
90 development, and by inference, resultant accumulation. Kocurek and Lancaster (1999)  
91 also suggested, within the multiple accumulation contexts proposed for dunefields in their  
92 concept of aeolian system sediment state, that dunefield activity could occur without  
93 resultant sediment accumulation, and when accumulation does occur, it can be temporally  
94 and spatially disjointed.

95

96 The assumption that autogenic drivers of accumulation exceed external forcing in  
97 influencing sediment accumulation in fluvial systems has been challenged by Macklin et al.  
98 (2012). This has been based on the limited numerical modelling and experimentation  
99 employed -'laboratory experiments using sand trays or rice piles' (Macklin et al.,  
100 2012:2165), that underpin the study of Jerolmack and Paola (2010), and the lack of

101 consideration of empirical data or 'Quaternary stratigraphic actualities' (Macklin et al.,  
102 2012:2165) in this and other critiques such as Van de Wiel and Coulthard (2010). Macklin  
103 et al. (2012) argue that at an appropriate scale, and with sufficient data, age control and  
104 stratigraphic knowledge, reliable archives of Quaternary environmental changes can be  
105 established from fluvial sedimentary records.

106

107 These same issues and considerations apply to aeolian systems. Jerolmack et al's (2012)  
108 study relates to a single, small (710 km<sup>2</sup>) North American dunefield, while Kocurek and  
109 Lancaster's (1999) theory was exemplified through the analysis of the even smaller  
110 (120km<sup>2</sup>) Kelso dunefield. Neither are necessarily representative of the extensive (often  
111 10<sup>3</sup>-10<sup>4</sup> km<sup>2</sup> in area) tropical-subtropical dune systems, many of which are dominated by  
112 linear dune forms rather than the more transient transverse dune forms found in the North  
113 American systems. Linear dunes are predominantly extending bedforms (Thomas 1992,  
114 Telfer 2011) that have the potential to store records of accumulation histories over long  
115 (multimillennial) timescales (Singhvi and Porat 2008). Localised surface sediment switching  
116 occurs on linear dunes in response to ongoing sediment transport processes during times  
117 of activity (*cf* Livingstone 1986, Tsoar 1983). Despite this, at the dunefield (as opposed to  
118 individual dune) scale there is a propensity towards accumulation being greatest during  
119 times of prolonged, externally forced, activity (Telfer et al. 2010, Bailey and Thomas 2014),  
120 but with the potential to be spatially discontinuous and with gaps in the recorded  
121 stratigraphy at any location (Kemp 2012). Thus palaeoenvironmental assessments of dune  
122 sedimentary records need to incorporate data from multiple locations, because information  
123 at any single location can be filtered out; but at the dunefield scale, when multiple records  
124 from individual dunes are combined, accumulation reflecting primary forcing is likely to be  
125 present (Bailey and Thomas 2014), as Macklin et al. (2012) note for fluvial archives too.

126

127 A difficulty that does exist with many dune sediment palaeoenvironmental interpretations is  
128 that they have relied on the luminescence ages themselves as the proxy of past conditions  
129 (Fig.1d) rather than utilising data that more closely relates to a physical aspect of dune  
130 system behaviour. As Singhvi and Porat (2008) rightly note, these ages need to be properly  
131 combined with stratigraphic and sedimentological data to extract palaeoenvironmental  
132 meaning. When ages are derived from sediments directly overlain or bracketed by, for  
133 example, palaeosols (e.g. Fitzsimmons et al. 2007a) or units of non-aeolian sediment (e.g.  
134 Atkinson et al. 2011a), it is possible to more firmly identify the timing of phases of aeolian  
135 activity. This is because the presence of the soil indicates a hiatus in aeolian deposition and  
136 acts as a stratigraphic marker between two phases of accumulation and/or indicates a  
137 cessation of accumulation of sufficient duration to allow soil development to occur.  
138 Likewise, basal ages from dune sediments sampled immediately above the contact with  
139 underlying strata provide an indication of when specific dune bodies began to accumulate in  
140 their present form (e.g. Telfer and Thomas 2008). This does not confer data on the first  
141 establishment of a dunefield, however, as dune overturn can erase a record of older  
142 accumulation, while dune extension, in the case of linear forms, means basal ages can  
143 differ along the length of a dune (Telfer 2011).

144

145 For most published dune sediment ages however, stratigraphical context is commonly  
146 limited, as the dated sediment simply forms part of a vertical and lateral continuum of sand.  
147 This can lead to criticisms of dune age data interpretation, especially when the number of  
148 dated samples is very limited (see for example Atkinson et al. 2011b for a critique of the  
149 dune accumulation histories inferred in Lancaster et al. 2002). Therefore a potential  
150 problem can arise of any small, or simply interpreted, age data set not capturing the 'real'

151 accumulation record preserved by the deposition of sediments. This issue, discussed by  
152 Leighton et al. (2013a), was exemplified by Stone and Thomas (2008) through the  
153 manipulation of a real dune age data set to simulate the impact of different sampling  
154 strategies on the resultant ages. Even where internal dune stratigraphies and structures are  
155 present and observable, allostratigraphical units (Hughes 2010) do not, at any single  
156 location, necessarily provide a clear indication of discrete depositional phases, as at this  
157 scale autogenic factors can influence the sediments that are preserved or subsequently  
158 removed as part of dune processes at the time of activity (Leighton et al. 2013b).

159

## 160 **Approach**

161

162 The issues considered above indicate that multiple records of sediment accumulation within  
163 a dunefield are needed as a start point to assess the longer term temporal patterns of  
164 accumulation. A recent study from Arabia (Leighton et al. 2014) has shown how age-  
165 controlled dune accumulation rate data can be assessed against independent proxies of  
166 climate and environmental dynamics, providing a useful approach for interpreting dune  
167 behaviour sensitivity and response to external forcing in the late Quaternary. We take this  
168 approach further, developing and applying a quantitative methodology for systematically  
169 establishing the timing of externally-forced sediment accumulation phases in dune fields.

170

171 We establish an analytical method for handling empirical dune age and accumulation  
172 records, based on the dune accumulation rate variability (ARV) data treatment model of  
173 Bailey and Thomas (2014). After detailing and testing the model, we collate published age  
174 and sediment accumulation data from two of the largest regional dune chronometric  
175 archives available, the southern hemisphere linear dunefields in Africa and Australia.

176 Using the revised accumulation model, new proxy data are generated to test against  
177 independent records of climate and environmental conditions that provide information on  
178 potential drivers of dune activity. While the focus is on the southern hemisphere, we do not  
179 include the numerous South American dunefields in this analysis, as collectively these have  
180 in total fewer than 80 published luminescence ages (Tripaldi et al 2016), often from  
181 geographically scattered contexts and with very few from any individual dunefield.

182

183 For the two study regions we chose data for the last 50ka, because of the relatively high  
184 number of dune age records available compared to earlier periods, and for linear dunes,  
185 which dominate these landscapes and preserve sedimentary records (up to  $10^5$  years)  
186 because of their developmental dynamics (Thomas 1992). These data allow us to consider  
187 whether hemispheric synchronicity in dunefield accumulation has occurred, as well as  
188 testing potential relationships between dune accumulation and external drivers using data  
189 from independent proxy records of climate and environmental change.

190

## 191 **Methods**

192

### 193 ***General considerations***

194 Numerical modelling provides a tool for interpreting dune records, potentially capturing the  
195 integrated effects of exogenic climate forcing, geomorphic processes that affect  
196 accumulation, including through autogenic behaviour, sampling and dating uncertainty, all  
197 of which control what is ultimately preserved in the resulting dune sediment record,  
198 effectively filtering the information available on past conditions. The conclusion from recent  
199 work (Telfer et al. 2010, Bailey and Thomas 2014) is that thicker preserved sedimentary  
200 units reflect periods of more intense aeolian activity, while spatial switching of depositional



201 and erosional sites on dune surfaces (Bristow et al. 2000) contributes to both discontinuous  
202 and spatially variable accumulation (Leighton et al. 2013). Further, preservation is expected  
203 to be skewed towards younger units, with the average thickness of preserved units  
204 reducing with time in proportion to  $1/\sqrt{age}$ , in the special case of normally-distributed  
205 random forcings; nonetheless, these results also allow for the preservation of relatively old  
206 sediments within the lower units of dune bodies. In this model, temporal gaps in records of  
207 accumulation can be due to wetter or less windy conditions, but may also result from  
208 sampling effects. Statistical uncertainty in luminescence dating results typically increases  
209 with age, and the resulting inability to resolve chronological events therefore ‘filters-out’  
210 older, higher frequency, events from the preserved sedimentary record (Bailey and Thomas  
211 2014).

212

213 The ‘Accumulation Rate Variability’ (ARV) method (Bailey and Thomas 2014) was found to  
214 provide a more robust and stratigraphically-appropriate approach to analysing records than  
215 other widely employed methods based on age frequencies (Thomas and Burrough 2012). It  
216 was necessary to modify the processes of the ARV model, to permit real measured  
217 luminescence ages to be added during the calculation process, leading to the  
218 determination and graphic output of the phases of dune accumulation represented in  
219 published dune age records.

220

### 221 ***Dune type, age and sediment thickness data***

222 The INQUA dune atlas database (<https://www.dri.edu/inquadunesatlas>) contains geo-  
223 referenced data for all published desert dune luminescence ages (Lancaster et al. 2016).  
224 All ages have a unique identifier code. Data on dune type, sampling context, sampling  
225 depth, dating method, age determination (dose rate, equivalent dose, etc) are included, as

226 well as final ages including their one sigma errors. We used the data available for the  
227 dunefields of southern Africa and Australia. Southern Africa has 624 published  
228 luminescence ages from dune sediments included in the database, of which 292 are from  
229 linear dunes, primarily from five continental interior dunefields (Thomas and Burrough  
230 2016). Australia has 689 ages, 450 from linear dunes, mainly in the eastern interior and  
231 southeastern regions of the country (Hesse 2016). All recorded sites are georeferenced in  
232 the database using information from the original published sources. For each dunefield,  
233 therefore, dune age and depth data are identifiable by location and site characteristics.  
234

235 For our analysis we extracted data that were derived from original studies of linear dunes.  
236 These commonly investigated dune sediments from locations at or close to dune crests,  
237 allowing in many cases the maximum thickness of dune sediments to be investigated.  
238 Analysis and sampling of sediments was either from hand or mechanically dug pits, or from  
239 sediment cores. The latter approach commonly utilised a hand or hydraulic auger fitted with  
240 light-tight sampling heads suitable for the requirements of luminescence dating (see e.g.  
241 Telfer and Thomas 2007 for sampling methodologies). Data suitable for our study were  
242 derived from five dunefields within the interior Kalahari of southern Africa (Figure 1a), which  
243 span today's SW-NE precipitation gradient (Thomas and Burrough 2012) and from four  
244 Australian dunefields: the Simpson, Strzelecki, Tirari and Mallee (Figure 2). For other  
245 dunefields, including the Namib in southern Africa and the Great Sandy Desert in Australia,  
246 data were insufficiently numerous to allow further analyses to occur in the context of this  
247 study.  
248

249 The linear dune age records for each dunefield were examined to establish data suitability.  
250 Records for any site where only a single age was available, or where the depth of sampling

251 was absent from the record, were excluded. For some individual sites, multiple ages and  
252 associated depth data were available, while some sites, usually from older studies that  
253 employed hand-dug pits for field sampling, yielded the minimum requirement of two ages,  
254 along with the sampling depths and distance between samples in the sediment profile. For  
255 each site, the sediment thickness between samples was calculated in centimetres. These  
256 data along with the mean and one sigma error of each associated luminescence age, were  
257 included in the final dataset. This created sets of paired age data, with associated  
258 accumulation thicknesses for each dunefield. Table 1 summarises the records extracted  
259 from the INQUA dune atlas data base that are used in the subsequent analyses in this  
260 study.

261

262 For southern Africa, the 114 linear dune accumulation intervals for the southern Kalahari  
263 dunefield were derived from data originally published in Thomas et al. (1997, three  
264 accumulation intervals), Stokes et al. (1997, two intervals), Bateman et al. (2003, six  
265 intervals), Telfer and Thomas (2007), which yielded 62 accumulation intervals from eight  
266 deep dune cores, one to a full dune depth of 14.5m giving 13 pairs of ages and associated  
267 depth data), and Telfer (2011, 41 intervals). The 43 accumulation intervals for the western  
268 Kalahari dunefield were derived from data originally presented in Stone and Thomas  
269 (2008), including four deep cores down to a maximum depth of 8.5m to the base of the  
270 dune. Data for the eastern dunefield were derived from Stokes et al. (1998, 21  
271 accumulation intervals) and Munyikwa et al. (2000, three intervals). Scarcer data for linear  
272 dune accumulation in the northeastern dunefield were from O'Connor and Thomas (1999,  
273 eight intervals) and for the northern dunefield six intervals were determined from the data in  
274 Thomas et al. (2000) and three from Thomas et al. (2003).

275

276 Data for the Simpson Desert dunes in Australia were derived from Nanson et al. (1992, 11  
277 accumulation intervals), Twidale et al. (2001, six intervals), Hollands et al. (2006, ten  
278 intervals) and Fujioka et al. (2009, 24 intervals). Of these, 20 of the accumulation intervals  
279 could be related to features regarded as fluvial source bordering linear dunes. All but 18 of  
280 the 71 accumulation intervals from Strzelecki Desert linear dunes come from source  
281 bordering linear dunes. Data were derived from Gardner et al. (1987, eight accumulation  
282 intervals), Coleman et al. (2002, four intervals), Lomax et al. (2003, eight intervals),  
283 Fitzsimmons et al. (2007a, 14 intervals, and 2007b 17 intervals), Nanson et al. (2008, six  
284 intervals), Cohen et al. (2010, 31 intervals) and Larson (2001, one interval). Fitzsimmons et  
285 al. (2007b) provided the data for 20 accumulation intervals from Tirari Desert linear dunes  
286 with the remaining two from Magee (1997). Accumulation data for the Mallee dunefield of  
287 southeastern Australia largely came from the study of Lomax et al. (2011) which generated  
288 61 accumulation intervals. The remainder were derived from Gardner et al. (1987) and  
289 Readhead (1988) with four intervals each, and three from Twidale et al. (2007).

290

### 291 ***Accumulation Intensity calculation***

292 There are a number of characteristics that would be favourable for any index of dune  
293 activity. These which are:

- 294 • the measure should increase as the accumulation rate increases;
- 295 • The index should not be affected by sampling resolution (i.e. it should not matter how  
296 many samples represent a unit of a given thickness within a given stratigraphic  
297 section);
- 298 • The index should penalize (i.e. give a lower score) as dating uncertainty increases;
- 299 • The strength of the measure should increase as more evidence is amassed for the  
300 presence of common units in different stratigraphic locations.

301 The approach to identifying periods of greater or lesser activity taken in many studies  
302 utilising age data from desert dune sediments (see Thomas and Burrough 2012 and 2016  
303 for discussion) is to calculate some density measurement of ages (as summed probability  
304 density functions or histograms). While this has some understandable logic, in that it  
305 identifies the presence of deposited material at the given age, such measures do not  
306 include information on accumulation, and are biased (linearly) by the sampling  
307 frequency/resolution (i.e. the 'signal' is in direct proportion to the resolution at which a given  
308 stratigraphic unit is sampled). The accumulation intensity method described below does not  
309 suffer these problems, and also possesses each of the favourable characteristics listed  
310 above.

311

312 Taking the information referred to above from dune chronometric studies in southern Africa  
313 and Australia, the first step involved analysing the data for each stratigraphic section in  
314 each dunefield. We took successive pairs of samples up through each sequence and  
315 calculated accumulation rates using the difference in depths between the samples and  
316 ages, re-sampled from within the one sigma dating uncertainties associated with each  
317 luminescence age. The ages were re-sampled (within their uncertainties) for calculation of  
318 the accumulation rates, while the ages as measured, with their actual stratigraphical  
319 contexts, were used for the chronological aspect of the index. The dispersion in these  
320 resampled accumulation rates (measured by the interquartile range) provides a proxy for  
321 the estimated accumulation rate. This method has an advantage over a simple measure of  
322 the gradient (between the mean ages of successive samples) by including the dating  
323 uncertainty, as well as providing a means of handling any apparent age inversions.

324

In detail, this method proceeded as follows. Input data for this process are arrays of depth  
 ( $d_{i,j}$ ), age ( $a_{i,j}$ ) and age uncertainty ( $e_{i,j}$ ), where  $i$  indexes sample number (deepest first,  
 with total sample number  $n_i^j$ ) and  $j$  indexes the core number (for the  $n_j$  cores). Depth data  
 are assumed to have no significant uncertainty. Each age  $a_{i,j} \pm e_{i,j}$  is resampled according  
 to  $a_{i,j}^* = a_{i,j} + r e_{i,j}$ , where  $r$  is a standard normal variate,  $r \sim N(0,1)$ , re-drawn for each date.  
 We then define  $\Delta a_{i,j}^* = a_{i+1,j}^* - a_{i,j}^*$ ,  $\Delta d_{i,j} = d_{i+1,j} - d_{i,j}$ ,  $A_{i,j} = \Delta d_{i,j} / \Delta a_{i,j}^*$ , where  $i \in$   
 $(1, n_i^j)$ ,  $j \in (1, n_j)$ .  $A_{i,j}$  is therefore a resampled (randomized) accumulation rate sampled  
 within the dating errors of successive depth samples  $i$  and  $i+1$ . This procedure is repeated  
 $n_c$  times for each  $i, i+1$  pair through each stratigraphic column of  $n_j$  dates (for the  $j^{\text{th}}$  'core').  
 The set of resampled accumulation rates for each core is  $A_{i,c}^j \in \Delta A_{i,j}$  ( $i \in (1, n_i^j)$ ,  $j \in (1, n_j)$ ,  
 $c \in (1, n_c)$ ). In addition we store the equivalent matrix,  $B$ , which contains the resampled  
 ages for each element of  $A$ , and also  $D$ , which contains the depth increments ( $\Delta d$ ) for each  
 element of  $A$ .  
 The time span of the analysis of all ages is  $[0, T]$ , and the time resolution ( $b$ ) at which  
 evaluations are made conforms to the condition  $T/b$  is an integer (the number of evaluation  
 intervals is  $n_t$ , and the index for each time increment is  $k \in [1, n_t]$ ).  
 We define a vector of accumulation rates that fall within each time interval, for core  $j$ ,  
 $\tilde{A}_k^j = A_{i,c}^j \forall A_{i,c}^j$  iff  $(B_{i,c}^j > t_k \text{ and } B_{i,c}^j \leq t_{k+1})$ ,  $k \in [1, n_k]$ ,  $j \in (1, n_j)$ . The total resampled  
 sediment accumulation is then defined  

$$A_{tot} = (\tilde{n} \sum_j \tilde{D}_k^j / n_c), \quad (\text{Eq.1})$$
 where  $\tilde{D}_k^j = D_{i,c}^j \forall D_{i,c}^j$  iff  $(B_{i,c}^j > t_k \text{ and } B_{i,c}^j \leq t_{k+1})$ ,  $k \in [1, n_k]$ ,  $j \in (1, n_j)$ . The dispersion of  
 the accumulation rates, for core  $j$  at time increment  $k$ , is then defined

349

350  $\gamma_k^j = IQR(\tilde{A})_z,$  (Eq.2)

351

352 where  $IQR()$  refers to the interquartile range, and  $z = (A_{tot}/(n_c b^2))$ . The accumulation  
353 intensity at each time interval is then the sum over all cores for each time interval  $t=kb$ , as  
354 shown in Eq.3. The large denominator in the units leads to small numerical values, and for  
355 the sake of convenience  $\gamma$  values are uniformly arbitrarily scaled by  $10^8$  in the data shown  
356 in this paper.

357

358  $\gamma_t = \sum_j \gamma_k^j.$  (Eq.3)

359

360

361 Figure 3 and Figure 4 provide examples of how the Accumulation Intensity ( $\gamma$  performs as  
362 key properties of the stratigraphic relationships are varied.

363

364 In Figure 3 we use the maximum (peak) intensity of  $\gamma$  ( $\gamma_{max}$ ) to demonstrate the behaviour  
365 of the signal as the relationship between age/depth is varied in a theoretical stratigraphy  
366 (see caption for further details). Figure 3(A) and (B) show that  $\gamma_{max}$  increases with  
367 sediment accumulation rate, as required.

368

369 As the accumulation rate depends on both the difference in age and difference in depth, we  
370 show the effect of independently varying both. Figure 3(A) shows a strong increase in  $\gamma_{max}$   
371 as the thickness of the dated unit is increased (whilst holding the ages constant). The non-  
372 linearity of the relationship means that thicker deposits are given proportionately greater  
373 prominence than thinner deposits; as required  $\gamma_{max} \rightarrow 0$  as  $\Delta d \rightarrow 0$ . Figure 3(B) shows how

374  $\gamma_{max}$  varies with the age difference between successive samples (with depths held  
 375 constant); here, again the asymptotic behaviour is as required,  $\gamma_{max} \rightarrow 0$  as  $\Delta a \rightarrow \infty$ , and  
 376  $\gamma_{max} \rightarrow 1$  as  $\Delta a \rightarrow 0$ . The insensitivity of  $\gamma_{max}$  to the sampling resolution (the number of  
 377 samples taken within a unit of fixed depth) is shown in Figure 3(C). Another requirement is  
 378 that  $\gamma_{max}$  should reflect the level of confidence in the data, and provide lower magnitude  
 379 signals in case where there is less confidence. We assume no uncertainty in the depth  
 380 measure, but include the dating uncertainty. Figure 3(D) shows the reduction in  $\gamma_{max}$  as  
 381 uncertainty increases, over the range typical for optical dating (7% being a good estimate of  
 382 the lowest uncertainty that can be obtained on a single absolute date, rising to 30% as a  
 383 typical maximum admissible dating uncertainty), with  $\gamma_{max} \rightarrow 0$  as  $e \rightarrow \infty$ . Not shown, but  
 384 clear from Eq.3, the effect of multiple instances of  $\gamma > 0$  for any given time period is  
 385 additive; that is, the signal is simply summed over multiple cores, and so synchronous units  
 386 observed multiple times will provide linearly increased signals.  
 387 Figure 4 provides examples of calculated  $\gamma_{max}$  for four different stratigraphic scenarios.  
 388 Figure 4(A) gives a sense of how the  $\gamma_{max}$  signal varies with unit thickness and dating  
 389 uncertainty (here all dates have a 10% error). Using Figure 4(A) as a reference, we see the  
 390 effect of doubling the errors to 20% in Figure 4(B), the effect of increasing sampling  
 391 resolution for the middle unit, in Figure 4(C), and the effect of decreasing the accumulation  
 392 rate (of the middle unit) in Figure 4(D).

393

394

395 **Application: Dunefield accumulation records over the last 50 ka and relation to**  
 396 **potential drivers**

397



398 Our new 'Accumulation Intensity' (*AI*) model allows, for each dunefield, accumulation  
399 intervals and accumulation rates (*AR*) to be calculated within the 50 ka time period that the  
400 chosen datasets cover. The integrated *AR* data from each dunefield, generated by  
401 combining the individual records from sampling sites within each dunefield, results in the  
402 production of *AI* curves through time. *AI* curves for each of the five southern African  
403 Kalahari dunefields are presented in Figures 5 and for the four Australian dunefields in  
404 Figure 6.

405

406 Qualitative comparisons between dunefields (of the form of the *AI* curve through time) are  
407 potentially highly instructive, but quantitative comparison of *AI* absolute magnitude is less  
408 straightforward as the factors that affect *AI* include the number of stratigraphic records  
409 available. Unlike 'date frequency' methods which tend to smear out signal peaks as  
410 additional data (dates) are added (see Thomas and Burrough 2016 for discussion), re-  
411 calculation of the *AI* as new dates become available can be expected to improve the  
412 analytical resolution of the individual dunefield curves, following the principles detailed in  
413 Bailey and Thomas (2014).

414

415 The dunefield *AI* curves can also be compared with selected independent proxy records of  
416 environmental and climate change pertinent to the regions where the dunefields occur. This  
417 provides the opportunity to assess potential relationships between dunefield accumulation  
418 and the behaviour of external drivers, including whether any covariance can be identified.  
419 These records are included in Figure 5 for southern Africa and in Figure 6 for Australia. In  
420 both plots, Vostok ice core temperature anomaly data (Petit et al. (1999) are shown as  
421 indicative of hemispheric-scale climate history over the last 50 ka, as well as austral  
422 summer solar insolation precession curves for 25°S.

423

424 ***Southern Africa***

425 As independent proxy data of regional environmental conditions we include the leaf wax  $\delta D$   
426 values from marine core MD96-2094 at 23°S in the southeast Atlantic, as this proxy is  
427 regarded as indicative of summer rainfall in the southern African interior (Collins et al.  
428 2014), and the excess air (%Ne) record from the Stampriet aquifer (Stute and Talma 1998),  
429 which relates to more southerly parts of the Kalahari. This aquifer directly underlies the  
430 western dunefield, with the %Ne proxy interpreted as a record of westerly-derived (probably  
431 winter) rainfall in the southwest interior. We chose these precipitation proxies over other  
432 more highly resolved records, for example geochemical data from laminated hyrax middens  
433 (e.g. Chase et al. 2010, 2011) , because the latter are derived from mountain sites to the  
434 west of the interior basin where the dunefields occur, and because records do not extend to  
435 the 50 ka of this investigation. We also include the SE Atlantic dust concentration record  
436 from marine core MD96-2094 at 20°S (Stuut et al. 2002), regarded as a proxy for easterly  
437 sector windiness,

438

439 Figure 5 shows that all Kalahari *AI* peaks, with the exception of late Holocene accumulation  
440 in the southern dunefield, occur during cooler times (Petit et al. 1999, Figure 5g) and on the  
441 declining limbs of February 25°S insolation (Figure 5h). As the latter has been interpreted  
442 as the driver of peak summer precipitation in the region, based on the leaf-wax  $\delta D$  record of  
443 Collins et al. (2014) (Figure 5d), this indicates that accumulation increases as climate  
444 becomes drier. With the exception of the northern Kalahari dunefield in western Zambia,  
445 which has an *AI* peak centred on 35 ka, the data for all other Kalahari linear dunefields  
446 show accumulation peaks after the last glacial maximum and within the 16-10 ka window.

447

448 Only the northern Kalahari dunefield lacks an *A/* peak after 35ka. This may have a climatic  
449 explanation in the sense that this northerly tropical dunefield is located in a region where  
450 drier excursions are less prevalent (Thomas and Burrough 2012). Post-accumulation  
451 degradation resulting from enhanced runoff (e.g. Flint and Bond 1968, McFarlane et al.  
452 2005) may also have removed the youngest sediments from the upper parts of dune  
453 bodies. Additionally, this *A/* curve has been derived from a relatively small number of  
454 suitable dune age records. We do not define a minimum number of samples that are  
455 required for the effective application of the *A/* method, since it is not simply the number of  
456 age records but their stratigraphic context, relationships to dune sedimentary profiles and  
457 coverage within a dunefield that are all important facets of 'completeness' and data  
458 suitability. Nonetheless, the data currently available may mean that the absence of younger  
459 peaks results from sampling issues. The timing of *A/* peaks for the other dunefields varies,  
460 broadly in a northeast (older) to southwest (more recent) direction. In parallel, the *A/* rising  
461 limbs in the eastern and northeastern dunefields commence in the late LGM, and later, at  
462 13.5ka, in the western and southern dunefields. The LGM is clearly not the focus of dune  
463 accumulation.

464

465 The relationship between dune accumulation, precipitation and summer insolation can be  
466 considered further in the context of the three northerly, tropical, Kalahari dunefields. These  
467 all occur downwind (west) of major fluvial systems, with peak accumulation recorded  
468 immediately after summer insolation maxima. It is posited that increases in accumulation  
469 after peak insolation (wet conditions) in these systems reflect dunefield development in  
470 contexts where sediment for dune building is significantly influenced by antecedent fluvial  
471 supply. The *A/* peaks for these dunefields do not however correspond with the peaks in SE  
472 Atlantic marine core dust accumulation (Figure 5f) off the west coast of southern Africa

473 (Stuut et al. 2002). When the general relationship of all Kalahari dunefield accumulation  
474 peaks is compared to the dust record, interesting observations emerge: *AI* peaks are  
475 broadly antiphase with high ocean dust accumulation. Stuut et al. (2002) regard the dust  
476 flux record as a proxy for windiness; however, studies of modern dust flux in southern Africa  
477 point towards strong associations between atmospheric dust and water-lain sediments  
478 (Thomas et al. 2017), including antecedent flooding of playa basin (Bryant et al. 2007) and  
479 river valley (Vickery and Eckardt 2013) source areas. Thus the dust record (Figure 5e) may  
480 not necessarily be a clear proxy for windiness but for source-area precipitation, a  
481 proposition that is borne out by the strong paralleling of trends with the leaf wax humidity  
482 record of Collins et al. (2014; Figure 5d).

483

484 In the western and southern Kalahari, increasing dunefield accumulation also coincides with  
485 declining summer insolation (Figures 5a & i), with peak *AI* values showing strong  
486 correspondence to both summer precipitation minima from the marine core  $\delta D$  record  
487 (Collins et al. 2014), and the Stampriet Aquifer precipitation record (Stute and Talma 1998).  
488 The mid-late Holocene is not a time of major accumulation in any Kalahari dunefield, but  
489 significant accumulation is recorded for the last 1.5 ka in the southern dunefield. The  
490 Stampriet record suggests reasonably wet, but drying, conditions through the Holocene,  
491 which may have generated sufficed vegetation to inhibit significant and prolonged dune  
492 activity. It can be noted that Holocene dune 'activity' is recorded in the raw luminescence  
493 ages for the southern and western dunefields shown in Figure 1b (data from Telfer and  
494 Thomas 2007 and Stone and Thomas 2008) but overall this appears not to have resulted in  
495 significant net sediment accumulation.

496

497 ***Australia***

498 There are surprisingly few independent and continuous precipitation proxy records relevant  
499 to the Australian interior, evident from the recent overview of Fitzsimmons et al. (2013). We  
500 therefore consider only the Tasman Sea dust accumulation record of Hesse (1994) from  
501 marine core E39-75 at 36°S, and the record of monthly Southern Ocean sea ice presence,  
502 considered to co-vary with the efficacy of easterly Trade Winds (Hesse 1994, Fitzsimmons  
503 et al. 2013).

504

505 Data for Australian linear dunefields show high spatial and temporal variability in *AI* peaks  
506 (Figure 6), with the earliest notable accumulation peak at 34 ka in the Strzelecki dunefield.  
507 For the temperate, southeastern, Mallee dunefield *AI* is greatest within 30-22ka, peaking at  
508 26 ka and 24 ka (Figure 6d). There is a moderate Tasman Sea dust peak in this general  
509 period at a comparable latitude (Figure 6e, Hesse 1994), though dune and dust peaks do  
510 not fully coincide and later dust peaks are not paralleled in the Mallee *AI* record. Other  
511 dunefields, in the Australian arid core, show a number significant accumulation peaks since  
512 25 ka. The Strzelecki is the only dune system with marked accumulation during the LGM,  
513 widely regarded as a peak in Australian aridity (Reeves et al. 2013). The Simpson,  
514 Strzelecki and Tirari systems all show *AI* peaks around 14-13 ka, with the former two  
515 dunefields also experiencing high *AI* from 12-10 ka, though there is a marked decline in the  
516 Strzelecki thereafter. As in the Kalahari, post-glacial peaks coincide with declining solar  
517 insolation (Fig 3i), but both the Simpson and Tirari also record significant Holocene *AI*  
518 peaks.

519

520 Australian fluvial source-bordering (FSB) dunes are shown as dashed curves in Figure 6a &  
521 b. We would expect FSB dune accumulation to occur during periods of highly seasonal flow  
522 or after wet phases, when sediment is available in fluvial systems for deflation by the wind.

Episodic or low fluvial flow has been recorded in the channel systems that flow into the Strzelecki during the LGM and at c.17-12 ka (Fitzsimmons et al. 2013). FSB *AI* records a peak in accumulation at this time, which is also evident, albeit in more subdued form, in non-FSB dunes. Overall, there is not a simple relationship in the relative timings of FSB and non-FSB dune accumulation. In the Simpson, FSB and non-FSB peaks are distinct. In the Strzelecki, the non-FSB peak at c13 ka and the FSB peak at 15 ka contrast with the previously mentions coincident peaks around the LGM and again at c 11 ka.

The Strzelecki is the only dunefield in this study where dune sediments are bracketed by palaeosols. These have provided a structural context for the interpretation of raw dune age data, and the identification of bracketed dune development phases at 35-32ka, 22-18 ka and 14-10 ka (Fitzsimmons et al. 2007b). This means of constraining dune development also provides an independent test of the *AI* record that is not afforded in the data from other dunefields. Figure 6 shows that our model generates *AI* peaks that correspond with these intervals.

## **Discussion**

The above analysis and application of the *AI* methodology raises several points of principle that are worth further consideration. These relate to the relationship between the range of ages in the 'parent' data set and the construction of *AI* peaks; implications of *AI* data for understanding the origins of today's dune bodies; and finally, the application of the methodology to other data sets.

***Why don't all ages in a dunefield record generate AI peaks?***

547 It is appropriate to consider why, for the last 50 ka, the *AI* curves for most of the Kalahari  
548 dunefields reduce the accumulation data, in effect, to a single or at most two peaks, some  
549 with secondary 'shoulders'. The *AI* curves contrast for example with the multiple peaks  
550 present in probability density function plots of dune age data (e.g. Telfer and Thomas 2007;  
551 Stone and Thomas 2008). We can explain this with reference to both the raw age data used  
552 to construct the curves (also see Thomas and Burrough 2016) and the original quantitative  
553 dune activity model of Bailey and Thomas (2013). The principles considered here are  
554 relevant to the data for all dunefields and for future applications of *AI* to other data sets.

555

556 First we can consider the available dune age and accumulation data. Figure 1b shows that  
557 in the southern Kalahari dunefield luminescence ages have been generated for the ~50-15  
558 ka period, but these ages do not result in peaks within the *AI* curve in Figure 5. In fact there  
559 are 16 ages recorded in the dune database for this period, from six sampling locations. Two  
560 of these include age inversions, and therefore cannot produce a meaningful associated  
561 accumulation thickness and were excluded from the analysis. Seven ages fall in the 21-29  
562 ka range and might be expected to produce an *AI* peak in the record, but even where four  
563 are derived from a stratigraphic sequence of 2m of sediment at one sampling location, the  
564 age errors (between 1.2 and 1.6 ka) plus an age inversion, effectively generate no net  
565 accumulation from the age cluster. Figure 7a) shows the same *AI* curve for the southern  
566 Kalahari as Figure 5a), while figure 7b) shows the same data with a higher resolution y axis,  
567 to vertically 'stretch' the lower part of the plot. This has the effect of magnifying the minor  
568 rises on the shoulders of the main *AI* peak centred on 10 ka, producing a very small 'peak'  
569 around c26ka. This is derived from the age and accumulation data generated in the model  
570 from the seven ages discussed above.

571

572 Five ages in the data set also fall in the 31-35 ka range, but as these come from four  
573 different sampling locations in the dunefield, they again do not permit the calculation of  
574 associated accumulation thicknesses. In essence, as sampled, the accumulated dune  
575 sands bracketed by ages in the 50-15 ka range make a minor contribution to the sediments  
576 of the southern Kalahari dunefield.

577

578 Second, we must also consider the underpinning principles of the model. The simulated  
579 dune activity forcings of Bailey and Thomas (2013) showed that overall dune accumulation  
580 is biased towards drier periods of time, since these have the greatest potential for erosion  
581 and deposition ('activity') to occur. In any period of activity the model also demonstrated  
582 that there is a net tendency for preservation of younger sediments (Figure 8 of Bailey and  
583 Thomas 2013). As sediment movement on dunes involves erosion and deposition  
584 interacting in response to aeolian processes, a new phase of activity in an existing dune  
585 system will result in the reworking of previously deposited sediments, as theorised by  
586 Kocurek (1998). In a dunefield subject to periods of alternating activity and inactivity in  
587 response to climate changes during the Quaternary, this will lead towards the preservation  
588 of sediments moved in more recent activity phases. In effect, following Kocurek and  
589 Lancaster (1999) and Jerolmack et al. (2012) autogenic processes can impact on the  
590 capacity of dune sediments, even those of extending linear forms, to preserve records of all  
591 phases of dune accumulation in the past. Experiment 6 of Bailey and Thomas (2013)  
592 demonstrated this phenomenon with respect to both alternating short dry phases and long  
593 wet phases, and vice versa (their Figure 13). We would expect, given the nature of linear  
594 dune sediment movement, erosion and accumulation, the preservation of evidence of  
595 earlier activity periods in the form of more isolated ages.

596



597 *Implications for today's dunefields*

598 This assessment has implications for understanding the system dynamics responsible for  
599 the dunefields that are found in the landscape today. Whether a dune system is active or  
600 inactive today, the sediments within constituent dune forms represent an archive of  
601 accumulation, over a single period, or multiple periods, of aeolian activity. The capacity of a  
602 dunefield to preserve a 'full' record of past activity or accumulation events is dependent on  
603 many factors, including the magnitude and duration of successive activity phases, and the  
604 supply of sediment within and to the dune system.

605

606 Where new sediment, *sensu* Kocurek (1998), is available for dune building during  
607 successive periods of activity, this may protect pre-existing sediments from reworking,  
608 limiting the capacity of autogenic processes to remove records of past accumulation  
609 phases. This *might* contribute to the greater number of *A1* peaks in several of the Australian  
610 dunefield records, where fluvial inputs to dunefields may bring new material for subsequent  
611 inclusion in dune sedimentary bodies. If palaeosols form on dune surfaces during times of  
612 quiescence, these may also serve to protect accumulated units from subsequent reworking  
613 during later phases of aeolian activity.

614

615 Consequently, the strong *A1* peaks recorded in the dune accumulation records of the  
616 southern and western Kalahari are likely indicative of significant phases of aeolian activity  
617 during the last 20 ka that have 'reset' the records accumulated from earlier phases of  
618 marked dune dynamism. This does not, as Bailey and Thomas (2013) modelled, indicate  
619 that significant older periods of dune activity did not occur; rather, their preservation in the  
620 sedimentary record is weak.

621

## 622 ***Application to other datasets and dune types***

623 In this study we have applied the *AI* methodology to dune age records from linear dune  
624 fields in two continents. The INQUA dune atlas database contains records from dunefields  
625 worldwide and from many different dune types. It is possible to apply this methodology to  
626 records from other dunefields, but to do so meaningfully will require careful consideration of  
627 the available data, and what records from dune types other than linear may mean in terms  
628 of past environmental dynamics and potential activity-drivers. Age records have to have  
629 stratigraphical context and sampling depth data to allow accumulation to be calculated.  
630 Preservation potential also varies according to dune type and respective dynamics;  
631 transverse forms are less likely to preserve accumulation at multi-millennial timescales  
632 because of the nature of their mobility, for example. Nonetheless, there is considerable  
633 potential to take forward the application of this methodology to other dune systems, and to  
634 reassess records as datasets for individual dune systems are added to.

635

## 636 **Conclusion**

637 Luminescence ages have for 35 years increased our capacity to unravel the environmental  
638 data stored in desert sand dunes, with these data contributing to Quaternary  
639 palaeoenvironmental reconstructions in regions often limited in other proxy records. The  
640 interpretation of dune age data sets has however often been enigmatic, and sometimes  
641 controversial. By developing a quantitative model, *AI*, that can process suitable age records  
642 into a more useful environmental parameter than raw ages alone, we can enhance the  
643 reading of dunefield age datasets. This model generates the potential to more effectively  
644 compare, test and explain histories of dunefield accumulation alongside the few other proxy  
645 records for desert systems, as well as generating a means to investigate the complex  
646 accumulation histories of dunefields.

647

648 Our analysis of southern African and Australian dunefield accumulation records shows that  
649 southern hemisphere linear dunefield development has not clearly co-varied, and is  
650 markedly variable within each continent, during the last 50 ka. Accumulation neither peaked  
651 during the LGM (Sarnthein 1978) nor shows consistent relationships to external global or  
652 hemispheric drivers of climate. In southern Africa most accumulation peaks are during  
653 cooler phases rather than in the Holocene, and a broad relationship with solar insolation  
654 procession can be inferred. This must be modulated by regional (e.g. windiness (Petit et al  
655 1999), precipitation (Stone and Thomas 2008, Collins et al. 2014) and local (e.g. sediment  
656 supply) factors since dunefield-to-dunefield variability in peak *AI* timings occur. At the  
657 regional and local level a lack of systematic proxy data for key modulating variables such as  
658 precipitation and sediment supply can hamper explanation, especially in Australia where,  
659 for example, there are limited data available for the timing of monsoon-driven river flow.

660

661 Overall our study suggests that major desert dunefields do not develop simply in response  
662 to variations in global forcing factors, and that the accumulation of the southern African and  
663 Australian dunefields for which data are available did not peak coevally at the LGM.  
664 Accumulation is more likely controlled by regional drivers moderated by local controls  
665 including fluvial system dynamics and sediment supply. Our ability to further test these  
666 assumptions in the future will not simply depend on generating more luminescence ages,  
667 though this is necessary for some under-sampled dune systems. It will also require  
668 appropriate and robust mechanisms for evaluating and interpreting the age data that result.  
669 In this paper we have developed, tested and applied one such approach that has the  
670 capability of integrating the array of factors that can influence the interpretation of ages in  
671 an environmentally meaningful manner.

672

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679

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901

902 **Figure captions**

903

904 **Figure 1.** a) The location of dunefields in southern Africa with published luminescence ages. b)

905 Kalahari luminescence age data by dunefield as mean ages with one sigma errors (upper) and

906 binary plots (lower), after Thomas and Burrough (2012). These plots illustrate the problems of

907 obtaining environmental interpretations from standard forms of age data presentation.

908

909 **Figure 2.** The location of dunefields in Australia with published age data.

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911

912 **Figure 3.** Example Accumulation Intensity (AI) signal behaviour under varying stratigraphic

913 relationships. All datapoints represent the maximum (peak) value of  $\gamma$ , normalized to unity, after

914 re-sampling different theoretical stratigraphies  $10^6$  times, at a time resolution of 200 yrs. The

915 cartoons above each sub-figure indicate the nature of the stratigraphic change under investigation.

916 In the case of (A), (B), (C), the stratigraphy consisted of two dates, with the initial condition of both

917 dates being  $10 \pm 1$  ka, at depths 2 m and 3 m. From here, changes in the stratigraphy were made to

918 generate the date shown: (A) the lower depth was increased, to vary the accumulation rate; (B) the

919 lower age was increased, to vary the accumulation rate; (D) the % error in both ages was varied,

920 hence wider abrs in the cartoon. In the case of (C), the outer sample ages were 12 m apart, and the

921 number of equally-spaced samples between these outer samples was increased.

922

923 **Figure 4.** Example signal behaviour under varying stratigraphic relationships. The  $\gamma$  data (shown in

924 red) were generated in an equivalent manner to those described in Figure 3, apart from in this case

925 the  $\gamma$  values are not normalized. The ages have associated 10% (at 1-sigma) uncertainties (2-sigma

error bars are shown), except for (B) which has 20% (at 1-sigma) uncertainties. Each value of  $\gamma$  is multiplied by  $10^8$  for numerical convenience, and this has no effect on the form of the results.

**Figure 5.** Accumulation intensity plots for the five Kalahari dunefields (a-c) and independent paleoclimate proxy records (see text for details). d) from Collins et al. 2014), e) from Stute and Talma (1998), f) from Stuut et al. (2002), g) from Petit et al. (1999). The grey bar represents the LGM (24-18 ka) as defined by Gasse et al. (2008).

**Figure 6.** Accumulation intensity plots for Australian dunefields (a-d). and independent proxy records representing potential regional to global drivers of climate controls: Dust accumulation in the Tasman Sea (36°S)) from marine core E39-75<sup>28</sup> (e); monthly Southern Ocean sea ice presence, co-varying with easterly Trade Winds<sup>26</sup> (f); Vostok ice core temperature anomalies<sup>23</sup> (h); February (summer) solar insolation procession at 25°S (i). There are not good temporally-extensive proxy records for precipitation from regions of Australia relevant to this study. The grey bar represents the LGM (24-18 ka) as defined by Gasse et al. (2008). In a) the three bars at the base of the AI curves show the dune accumulation phases identified by Fitzsimmons et al. (2007b) as bracketed by palaeosols within dune bodies.

**Figure 7.** Accumulation intensity plots for the southern Kalahari dunefield: a) with full AI index values in the vertical axis, and b) with y axis scaled to show lower intensity accumulation ‘peaks’.

947 Table 1. Published age data used in this analysis, including from fluvial and lacustrine sediment  
948 source-bordering (FSB) linear dunes in Australia. 'Accumulation intervals' are pairs of ages with  
949 accompanying depth data, allowing accumulation intensity *AI* to be calculated.  
950

	Total no. dune lum. ages	Linear dune ages	<i>Fluvial /lake source bordering</i>	Accumu- lation intervals
<b>Southern Africa</b>	<b>624</b>	<b>292</b>		
Kalahari	387	254		
southern		136		114
western		47		43
eastern		33		24
northern		19		9
northeastern		19		8
<b>Australia</b>	<b>689</b>	<b>450</b>		
Simpson	95	92	<i>20</i>	71
Strezelecki	156	129	<i>120</i>	89
Tirari	39	30	<i>28</i>	22
Mallee	130	113	<i>10</i>	72

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