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1 Title of manuscript: Quantitative analysis of the sedimentary architecture of eolian  
2 successions developed under icehouse and greenhouse climatic conditions

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## 6 **ABSTRACT**

7 The continental terrestrial record preserves an archive of how ancient sedimentary systems respond to and  
8 record changes in global climate. A database-driven quantitative assessment reveals differences in the  
9 preserved sedimentary architectures of siliciclastic eolian systems with broad geographic and stratigraphic  
10 distribution, developed under icehouse versus greenhouse climatic conditions. Over 5,600 geological entities,  
11 including architectural elements, facies, sediment textures and bounding surfaces, have been analyzed from  
12 34 eolian systems of Paleoproterozoic to Cenozoic ages. Statistical analyses have been performed on the  
13 abundance, composition, preserved thickness, and arrangement of different eolian lithofacies, architectural  
14 elements and bounding surfaces. Results demonstrate that preserved sedimentary architectures of icehouse  
15 and greenhouse systems differ markedly. Eolian dune, sandsheet and interdune architectural elements that  
16 accumulated under icehouse conditions are significantly thinner relative to their greenhouse counterparts; this  
17 is observed across all basin settings, supercontinents, geological ages, and dune-field physiographic settings.  
18 However, this difference between icehouse and greenhouse eolian systems is exclusively observed for  
19 paleolatitudes <30°, suggesting that climate-induced changes in the strength and circulation patterns of trade  
20 winds may have partly controlled eolian sand accumulation. These changes acted in combination with  
21 variations in water-table levels, sand supply and sand transport, ultimately influencing the nature of long-term  
22 sediment preservation. During icehouse episodes, Milankovitch-cyclicity resulted in deposits typified by  
23 glacial accumulation and interglacial deflation. Greenhouse conditions promoted the accumulation of eolian  
24 elements into the geological record due to elevated water tables and biogenic and chemical stabilizing agents,

25 which could protect deposits from wind-driven deflation. In the context of a rapidly changing climate, the  
26 results presented here can help predict the impact of climate change on Earth surface processes.

27 **Keywords:** Eolian, Database, Icehouse, Greenhouse, Climate

## 28 INTRODUCTION

29 The current rate of release of carbon dioxide into the atmosphere, largely through the anthropogenic  
30 combustion of fossil fuels, is occurring at a geologically unprecedented rate (Kidder and Worsley, 2011;  
31 Andrew, 2020; Peters et al., 2020). The associated changes in global climate, and the impact of such climate  
32 change in terms of its influence on Earth surface processes, has significant scientific and societal implications  
33 (e.g., IPCC, 2007 and references therein). Quantifying the response of Earth's geosphere to changes in climate  
34 therefore represents one of the foremost issues faced in modern sedimentology (Hodgson et al., 2018). Given  
35 the paucity of long-term (> 100 years) instrumental records, analysis of the sedimentary record is critical for  
36 understanding the impact of climate change on Earth surface processes. The continental terrestrial record  
37 preserves an archive of how ancient sedimentary systems respond to, and record, changes in global climate,  
38 over time scales far beyond the range of human experience. Observational evidence from the ancient  
39 sedimentary record therefore provides a means to both quantify past responses and predict future responses of  
40 the Earth's surface processes to shifts in global climate.

41 Throughout geological history, the Earth's climate can be subdivided into periods characterized by the  
42 presence or absence of major continental ice-sheets and polar ice (Fig. 1) – two climate states referred to as  
43 icehouse and greenhouse, respectively (Frakes et al., 1992; Price et al., 1998; Cromwell, 1999). The preserved  
44 eolian sedimentary record, which spans over three billion years of Earth history from the Archean to the  
45 present day (Clemmensen, 1985; Dott et al., 1986; Voss, 2002; Cather et al., 2008; Simpson et al., 2012;  
46 Rodríguez-López et al., 2014) is a valuable archive of the continental landscape response to periodic  
47 fluctuations between icehouse and greenhouse worlds.

48 A comprehensive global-scale quantitative comparison of the preserved architectures of sand-dominated  
49 eolian sedimentary systems (ergs, *sensu* Wilson, 1973) accumulated and preserved under icehouse and  
50 greenhouse conditions has not been undertaken previously. Prior research on this topic has been primarily

51 reported in the form of largely qualitative accounts, commonly for individual case studies or regions from  
52 eolian successions associated with either greenhouse (e.g., Crabaugh and Kocurek, 1993; Kocurek et al., 1992;  
53 Jones and Blakey, 1997; Benan and Kocurek, 2000; Kocurek and Day, 2018) or icehouse (e.g., Cowan, 1993;  
54 Meadows and Beach, 1993; Clemmensen and Abrahamsen, 1983) climatic conditions.

55 In addition to the effects of climate, eolian sedimentary systems are sensitive to a variety of additional forcings,  
56 including rate and type of sediment supply, sea level, tectonic configuration, basin setting and dune-field  
57 physiographic setting (e.g., Blakey and Middleton, 1983; Blakey, 1988; Mountney et al., 1999; Kocurek et  
58 al., 2001; Nichols, 2005; Soria et al., 2011). As such, isolating and quantifying the global effects of climate as  
59 a control on sedimentary systems is difficult, especially for individual case studies. To address this problem,  
60 this study uses a global dataset derived from 42 published articles associated with 34 ancient eolian  
61 successions (Fig. 1).

62 The aim of this study is to quantify relationships between global climate states and preserved eolian  
63 sedimentary architecture at multiple scales of observation. This study addresses three main research questions:  
64 (i) How are the characters of preserved eolian and related architectural elements, and their bounding surfaces  
65 affected by fluctuations in global climate states? (ii) Does the prevailing global climate influence the  
66 sedimentology and stratigraphic architecture of preserved eolian sedimentary successions? (iii) Can the effects  
67 of icehouse and greenhouse conditions on preserved eolian sedimentary architectures be isolated from those  
68 of supercontinental setting, paleolatitude, basin setting and dune-field physiographic setting?

## 69 **Background: an Overview of the Icehouse and Greenhouse Earth**

70 Icehouse and greenhouse conditions account for approximately 15% and 85% of Earth history, respectively  
71 (Fig. 1; Frakes et al., 1992; Crowell, 1999; Link, 2009). Global shifts between icehouse and greenhouse  
72 conditions are caused by the cumulative effects of astronomical, biogeochemical and tectonic events, which  
73 interact with each other and lead to the development of feedback mechanisms that act to influence global  
74 climate. Icehouse and greenhouse conditions are respectively defined by the presence or absence of major  
75 polar ice-sheets that calve marine icebergs (Kidder and Worsley, 2012). Greenhouse conditions can, however,

76 be associated with seasonal sea ice, alpine glaciers and transient polar ice-caps (Frakes, 1992; Kidder and  
77 Worsley, 2012).

78 Five major icehouse periods are recognized in Earth history (Fig. 1): the Huronian (2400-2100 Ma; Coleman,  
79 1907; Evans et al., 1997), the Cryogenian (720-635 Ma; Knoll and Walter, 1992; Bowring et al., 2003;  
80 Hoffman et al., 2004), the Late Ordovician and Early Silurian glaciations, also known as the Andean-Saharan  
81 (450-420 Ma; Brenchley et al., 1994), the Late Paleozoic (360-260 Ma; Montanez and Poulsen, 2013;  
82 Godd ris et al., 2017), and the current Cenozoic icehouse conditions that persist today (since 33.9 Ma; Frakes  
83 et al., 1992). The five major icehouse intervals have each lasted for tens of millions of years and are each  
84 associated with mid-latitude glaciation down to sea level (Frakes et al., 1992; Cromwell, 1999). Relative to  
85 greenhouse conditions, icehouse conditions are typically associated with: (i) lower atmospheric levels of  
86 carbon dioxide; (ii) lower sea levels and sea-surface temperatures; (iii) strong thermohaline deep-ocean  
87 circulation; (iv) strong marine polar-to-equatorial thermal contrasts; (v) increased wind velocities at low-  
88 latitudes ( $< 30^\circ$ ) leading to higher wind shear and higher wind-related erosive power (Fig 2; Frakes et al.,  
89 1992; Cromwell, 1999; Forster et al., 2007; Kidder and Worsley, 2010, 2012).

90 Within long-lived icehouse periods, climatic conditions are known to fluctuate between glacial and interglacial  
91 episodes, which give rise to the waxing and waning of continental glaciations; these cycles of glacial  
92 expansion and retreat are superimposed onto overall longer-term net icehouse conditions. In the most recent  
93 Cenozoic icehouse, glacial and interglacial cycles occur at quasi-100 kyr intervals, with shorter 41 kyr and 21  
94 kyr quasi-cycles superimposed (Shackleton et al., 1999). The cyclic regularity of glacial and interglacial  
95 periods is attributed dominantly to variations in the Earth's orbital parameters – the so-called Milankovitch  
96 cyclicity. The effects on the sedimentation of glacial and interglacial oscillations are well documented in the  
97 deep-sea sedimentary record (e.g., Rea and Janeck, 1981; Hovan et al., 1991; Petit et al., 1991; Winckler et  
98 al., 2008). For example, eolian dust supply to the deep sea is greater under glacial conditions, relative to  
99 interglacial conditions (e.g., Woodard et al., 2011), as a consequence of heightened aridity and stronger wind  
100 strengths during glacial episodes.

## 101 **METHODOLOGY**

## Case Studies and Associated Metrics

Thirty-four case studies, each representing an ancient eolian sedimentary succession (Fig. 1, Table 1), and associated with detailed datasets from 42 published articles, have been analyzed using the Database of Aeolian Sedimentary Architecture (DASA). DASA is a relational database that stores data on a variety of eolian and associated non-eolian entities relating to different scales, including architectural elements, lithofacies and bounding surfaces. DASA records both qualitative and quantitative attributes that characterize the type, geometry, spatial relations, hierarchical relations, temporal significance, and textural and petrophysical properties of eolian and related depositional units and their bounding surfaces. In this study, architectural elements, facies elements, textural properties and eolian bounding-surface types documented from the selected case-study examples are analyzed.

For this investigation, of the 42 scientific articles considered, 24 provide accounts of systems developed under icehouse conditions and 18 of greenhouse systems. Of the 34 case studies, 20 represent icehouse conditions and 14 represent greenhouse conditions. In total, 5,598 geological entities representing architectural and facies elements, textural observations and eolian bounding surfaces have been analyzed: 2,772 relate to sedimentary successions interpreted as having accumulated under the influence of icehouse climatic conditions; 2,826 under greenhouse conditions. Observations can be further categorized as follows: (i) 2,578 eolian and associated non-eolian architectural elements have been analyzed, of which 1,156 and 1,422 architectural elements relate to icehouse and greenhouse case-study systems, respectively; (ii) 985 eolian facies units have been analyzed, of which 630 and 355 facies relate to icehouse and greenhouse case-study systems, respectively; (iii) 1,308 textural observations have been analyzed, of which 749 and 559 relate to icehouse and greenhouse case-study systems, respectively; (iv) 727 bounding surfaces have been analyzed, of which 237 and 490 relate to icehouse and greenhouse systems, respectively.

Each examined case study has associated metadata describing its geological background and the boundary conditions present at the time of deposition; these metadata include the prevailing climate, basin setting, geologic age and paleosupercontinental setting. Metadata are derived from the original source work and additional published literature.

128 Architectural elements are defined as distinct sedimentary bodies with characteristic sedimentological  
129 properties (e.g., internal composition, geometry), and are the products of deposition in a specific sub-  
130 environment (e.g., a dune, a wet interdune, or a fluvial channel; for definitions see Table 2). Facies elements  
131 are defined as sedimentary bodies differentiated on the basis of sediment composition, texture, structure,  
132 bedding geometry, fossil content, or by the nature of their bounding surfaces (cf. Colombera et al., 2012,  
133 2016).

134 At the scale of architectural and facies elements, each element is assigned an interpretation derived from the  
135 original source work (e.g., a dune set at the architectural-element scale, or adhesion strata at the facies-element  
136 scale). For each architectural and facies element, geometric properties (element thickness, length and width)  
137 are also recorded. However, in this investigation, the only geometric parameter considered in detail is the  
138 thickness of the deposit.

139 The textural properties considered here are grain size, sorting and roundness. For all textural properties, if a  
140 numerical value is not assigned in the original source work, but a descriptive term is provided (e.g., fine-  
141 grained sand), classes are converted into numerical values according to the schemes of Folk and Ward (1957)  
142 for grain size and sorting, and to the Krumbein scale of roundness (Krumbein, 1941).

143 The following types of qualitative data regarding super-bounding surfaces (supersurfaces) are considered here:  
144 (i) a classification of surface type (i.e., environmental significance) according to the schemes of Fryberger  
145 (1993) and Kocurek (1996); (ii) the association of features (sedimentary structures) indicative of substrate  
146 conditions (e.g., dry, damp, wet) and associated with the state of the surface; and (iii) the occurrence of features  
147 indicative of surface stabilization (e.g., Ahlbrandt et al., 1978; Loope, 1988; Basilici et al., 2009, 2020; Dal'  
148 Bo et al., 2010; Krapovickas et al., 2016).

### 149 **Dating Ancient Eolian Successions**

150 Ancient eolian successions can be difficult to date in absolute terms due to a general paucity of features  
151 suitable for numerical age-dating (Rodríguez-López et al., 2014). As such, determining the time when an  
152 eolian succession accumulated can be challenging. Some eolian deposits closely associated with (i) extrusive  
153 volcanics, (ii) fossil-rich marine interbeds, or (iii) abundant micro-fossils present in the eolian deposits

154 themselves, can be dated and assigned a geochronometric or biostratigraphic age. More commonly, however,  
155 only a relative age can be established, such that eolian successions might be interpreted in terms of sequence-  
156 stratigraphic or climate-stratigraphic contexts (e.g., Mountney and Howell, 2000; Atchley and Loope, 1993;  
157 Jordan and Mountney, 2010, 2012). Many eolian successions contain surfaces that are thought to represent  
158 and record multiple long-lived depositional hiatuses in accumulation, associated with the formation of  
159 supersurfaces (e.g., Loope, 1985). For many eolian systems, the amount of time represented by such  
160 supersurfaces is likely significantly greater than that represented by the eolian accumulations themselves;  
161 eolian successions may be representative of only a small amount of the total geological time over which the  
162 eolian system was active (Loope, 1985; cf. Ager, 1993; Sadler, 1981). The preserved sedimentary record of  
163 eolian systems is highly fragmentary and age ranges of eolian deposits reported in the literature may be over-  
164 or under-estimates; accurately determining the ages of ancient eolian successions represents therefore an  
165 unavoidable caveat.

166 For this analysis, examined case studies have been assigned to a binary ‘icehouse’ or ‘greenhouse’  
167 classification scheme. Despite the above-discussed limitations on dating eolian successions, given that major  
168 icehouse and greenhouse episodes span (many) tens of millions of years, placing eolian successions within in  
169 an ‘icehouse’ or ‘greenhouse’ category can be achieved with confidence; this study requires only that the age-  
170 range of each eolian succession considered in the analysis generally falls within episodes classed as icehouse  
171 or greenhouse climate states (Frakes et al., 1992; Crowell, 1999; Link, 2009). As such, precise absolute ages  
172 for eolian successions considered in this analysis are not crucial.

173 Determining the age-ranges of Precambrian eolian successions can, however, be more challenging, since their  
174 ages are typically more difficult to constrain (e.g., Pulvertaft, 1985; Simpson et al., 2012) and they cannot  
175 necessarily be reliably assigned to an ‘icehouse’ or ‘greenhouse’ climate category. Only Precambrian eolian  
176 successions with age-ranges that fall into to an ‘icehouse’ or ‘greenhouse’ category have been included in the  
177 analysis. In the analysis and discussion all Precambrian icehouse examples are compared against all  
178 Precambrian greenhouse examples.

179 There also exist eolian successions that record evidence of system development in a transitional state between  
180 icehouse and greenhouse worlds (see Eriksson et al., 2019). Such examples cannot readily be assigned to the  
181 binary icehouse-greenhouse classification scheme used in this study. Given that the focus of this study on the  
182 eolian sedimentary signature of climate extremes, examples of these “transitional” eolian successions have  
183 not been included in this investigation.

### 184 **Carbonate Eolian Systems**

185 In this investigation, siliciclastic-dominated eolian successions have been studied; carbonate-dominated eolian  
186 successions are not considered. Carbonate-dominated eolian successions (eolianites) most commonly develop  
187 along humid, mid-high latitude coasts, and along arid to semi-arid, mid-low latitude coasts that neighbor  
188 carbonate platforms (Clemmensen et al., 1997; Brooke, 2001; Nielsen et al., 2004; Simpson et al., 2004;  
189 Frébourg et al., 2008; Fornós et al., 2009; Andreucci et al., 2010). Carbonate-dominated eolian successions  
190 commonly undergo early post-depositional modification, notably via the precipitation of early diagenetic  
191 calcitic cements, which can readily stabilize original dune topography (Pye, 1983; Simpson et al., 2004; Guern  
192 and Davaud, 2005). As such, processes of deflation, construction, accumulation and preservation in carbonate  
193 eolian systems are markedly different to those of most siliciclastic eolian systems. In particular, dune deflation  
194 can be retarded, and dune stabilization and accumulation can be enhanced by early diagenetic cementation.  
195 Mechanisms of preservation of carbonate-dominated eolian deposits in relation to prevailing climatic and  
196 sediment supply conditions differ considerably from those of siliciclastic-dominated systems (Rodríguez-  
197 López et al., 2014). For these reasons, this study only considers siliciclastic-dominated eolian systems and  
198 their deposits.

### 199 **Statistical Analysis**

200 Quantitative data, including element thickness, grain size, sorting and grain roundness have been subject to  
201 statistical analysis. One-tail t-tests have been undertaken to determine if a significant difference exists between  
202 the means of icehouse and greenhouse groups. To test for statistical significance of differences among multiple  
203 groups (i.e. for the example considering multiple supercontinents under greenhouse conditions), analysis of  
204 variance (ANOVA) is applied. Post-hoc tests, using a Bonferroni correction, are applied to t-tests and ANOVA

tests alike. An  $\alpha$  value of 0.05 is considered for all statistical analyses; a family-wise alpha is considered when applying the Bonferroni correction.

## RESULTS

Table 3 provides a summary of results of statistical analyses discussed in the text; this includes mean, median, standard deviation, and number of observations for variables of interest (eolian and related element thicknesses, grain size, sorting and roundness), and the results of statistical tests. In the text, for brevity only mean values are reported.

### Eolian Elements

Differences in the characteristics of eolian and associated non-eolian architectural elements are considered first (Table 2). The relative proportion of types of eolian and non-eolian architectural elements is determined based on total element counts: eolian architectural elements form 63% and 62% of architectural elements in the studied successions accumulated under icehouse and greenhouse conditions, respectively (Fig. 3A). For all architectural elements classified as ‘eolian’ (Table 2), statistically significant differences in element thickness are found; icehouse eolian architectural elements are significantly thinner than greenhouse eolian elements, with mean values of element thickness of 2.36 m and 5.47 m, respectively (Fig. 4A; Table 3).

Of the total recorded eolian architectural elements, the percentages of elements classified as ‘dune set’, ‘sandsheet’ and ‘interdune’ are considered further (Fig. 3B; for definitions see Table 2). Dune sets form 62% and 82% of all recorded observations for icehouse and greenhouse eolian successions, respectively (Fig. 3B). Sandsheets form 20% and 12% of icehouse and greenhouse eolian successions, respectively (Fig. 3B). Interdunes form 18% and 4% of the icehouse and greenhouse successions, respectively (Fig. 3B). All three major eolian architectural element types (dune sets, sandsheets and interdunes) show statistically significant differences in mean element thickness (Fig. 4B-D; Table 3). Under icehouse conditions, dune sets, sandsheets and interdunes have mean thicknesses of 3.67 m, 0.55 m and 0.88 m, respectively (Table 3). Under greenhouse conditions, dune sets, sandsheets and interdunes have mean thicknesses of 5.93 m, 4.15 m and 2.00 m, respectively (Fig. 4B-D; Table 3).

230 Interdune elements are considered further and subdivided into ‘wet’, ‘damp’, and ‘dry’ types (*sensu* Kocurek,  
231 1981) (Fig. 5A; for definitions see Table 2). In successions developed under icehouse conditions, 15% of  
232 interdune elements are of wet type, 48% are of damp type, and 37% are of dry type. In greenhouse successions,  
233 60% of interdune elements are of wet type, 30% are of damp type, and 10 % are of dry type (Fig. 5A).

### 234 **Non-Eolian Architectural Elements**

235 The percentage of recorded non-eolian architectural elements reported for the studied successions is similar  
236 across icehouse and greenhouse successions, forming 37% and 38% of recorded observations, respectively  
237 (Fig. 3C). Under both icehouse and greenhouse conditions, alluvial and fluvial deposits are the most common  
238 non-eolian element types. Greenhouse successions are associated with a greater percentage of sabkha elements  
239 (14% vs 1%). Across icehouse and greenhouse successions, there is no statistically significant difference in  
240 the mean thickness of non-eolian architectural elements of any type (Table 3).

### 241 **Eolian Facies Elements**

242 In greenhouse successions, interdune elements of any type are most likely composed of adhesion strata (92%)  
243 and plane-bed lamination (8%) (Fig. 5B). In icehouse successions, a greater variety of facies-element types  
244 are recorded, including adhesion strata (38%), subaqueous ripples (27%), plane-bed lamination (19%), wind-  
245 ripple lamination (14%) and deflation-lag strata (2%). Icehouse sandsheet elements are dominated by adhesion  
246 strata (30%), deflation-lag strata (28%) and wind-ripple strata (27%), whereas greenhouse sandsheet elements  
247 mostly comprise wind-ripple strata (61%) and interfingered strata (30%) (Fig. 5C; interfingered strata  
248 comprise intercalated deposits of wind-ripple, grainflow, grainfall and/or plane-bed strata in varying  
249 proportions – Table 2). In icehouse successions, facies elements of any type are significantly thinner than  
250 those in greenhouse successions (mean thickness of 2.20 m vs 7.53 m; Fig. 4E; Table 3). For descriptions of  
251 facies units see Table 2.

### 252 **Eolian Texture**

253 The textural properties of all eolian architectural and facies elements are now considered. Systems developed  
254 under icehouse and greenhouse conditions have mean values of modal grain size of 0.34 mm and 0.36 mm  
255 (both medium sand; Fig. 6A); the difference between these values is not statistically significant (Table 3).

256 Icehouse systems are characterized by a higher median value of modal grain size of 0.38 mm (medium sand),  
257 relative to 0.25 mm (fine-to-medium sand) for greenhouse systems (Fig. 6A).

258 In both icehouse and greenhouse systems, eolian sands are, on average, moderately well sorted (icehouse =  
259 0.57  $\sigma$ , greenhouse = 0.58  $\sigma$ ; Fig. 6B); there is no statistically significant difference between mean values of  
260 sorting (Table 3). There is, however, a statistically significant difference in mean values of grain roundness  
261 between icehouse (mean = 0.57 K: rounded) and greenhouse (mean = 0.77 K: well-rounded) eolian sands (Fig.  
262 6C) (Table 3). Thus, greenhouse conditions are associated with increased sand-grain textural maturity relative  
263 to icehouse conditions.

## 264 **Eolian Surfaces**

265 Eolian supersurfaces are recorded from 12 systems; 6 each represent icehouse and greenhouse conditions.

### 266 *Supersurface Spacing*

267 The average supersurface spacing is calculated by measuring the vertical distance between two successive  
268 supersurfaces. Under icehouse conditions the mean spacing is 16.34 m (standard deviation = 12.70 m; Table  
269 3); under greenhouse conditions the mean spacing is 9.07 m (standard deviation = 6.34 m; Table 3). This  
270 indicates that supersurfaces are more widely spaced under icehouse conditions relative to greenhouse  
271 conditions; however, icehouse supersurfaces exhibit greater variability in supersurface spacing.

### 272 *Supersurface Descriptions*

273 Supersurfaces present in icehouse successions are classified dominantly as deflationary (88%) and  
274 subordinately as bypass surfaces (12%) (Fig. 7A). In greenhouse systems, deflationary and bypass  
275 supersurfaces form 67% and 33% of recorded supersurfaces, respectively (Fig. 7A). The nature of the substrate  
276 associated with the supersurfaces also varies considerably between icehouse and greenhouse examples.  
277 Icehouse supersurfaces are dominantly associated with features indicative of a wet surface (86%) and only  
278 rarely of a damp (6%) or dry (8%) surface. By contrast, in greenhouse successions, dry, damp and wet surface  
279 types are associated with 12%, 24% and 64% of recorded supersurfaces, respectively (Fig. 7B). When the  
280 nature of stabilization of supersurfaces is considered, 62% of icehouse supersurfaces are classified as

281 unstabilized and 38% as stabilized; for greenhouse conditions, unstabilized and stabilized supersurfaces  
282 comprise 85% and 15% of recorded supersurfaces, respectively (Fig. 7C).

### 283 **Non-Climatic Controls**

284 In addition to climate, other controls might influence the preserved style and geometry of sedimentary  
285 architectures in eolian systems (e.g., Blakey and Middleton, 1983; Blakey, 1988; Mountney et al., 1999;  
286 Kocurek et al., 2001; Nichols, 2005; Soria et al., 2011). To better discriminate the influence of icehouse and  
287 greenhouse conditions, these other factors must be considered. To this end, where data are available,  
288 comparisons between icehouse and greenhouse conditions are made for: (i) specific paleogeographical  
289 configurations and geological age, (ii) basin setting, (iii) paleolatitude, and (iv) dune-field (erg) physiographic  
290 setting. In the following analyses, the thicknesses of eolian architectural elements (cross-strata packages, dune  
291 sets, dune cosets, dune compound sets, sandsheets and interdunes) are considered.

### 292 *Paleogeography and Geological Age*

293 Two supercontinental paleogeographic configurations spanned both icehouse and greenhouse times: those  
294 associated with Precambrian supercontinents (Rodinia and Columbia), and Pangea; the number of case studies  
295 falling into these categories are 6 and 11, respectively. When evaluated separately for the Precambrian and  
296 Pangean supercontinental settings, statistically significant differences between the mean thickness of eolian  
297 architectural elements deposited under icehouse and greenhouse conditions are seen (Table 3). The mean  
298 thickness of Precambrian architectural elements is 1.43 m and 5.03 m for icehouse and greenhouse  
299 successions, respectively (Fig. 8A), whereas the mean thickness of Pangean architectural elements is 3.41 m  
300 and 6.85 m for icehouse and greenhouse conditions, respectively (Fig. 8A; Table 3).

### 301 *Basin Setting*

302 Of the case-study examples examined in this study, eolian systems deposited under icehouse and greenhouse  
303 conditions are both recognized in the infill of sedimentary basins classified as intracratonic (sag) basins,  
304 continental rifts, and foreland basins (for definitions see Table 2); the number of case studies falling into these  
305 categories are 17, 4, and 3, respectively. For each of these basin types, there exists a statistically significant  
306 difference between the mean values of the thicknesses of eolian architectural elements deposited under

307 icehouse and greenhouse conditions (Table 3). Architectural elements accumulated under icehouse conditions  
308 in intracratonic, rift and foreland basins yield mean thickness values of 1.73 m, 0.70 m and 2.11 m, respectively  
309 (Fig. 8B). Greenhouse architectural elements in intracratonic, rift and foreland basins instead return mean  
310 thickness values of 7.63 m, 2.48 m and 4.23 m, respectively (Fig. 8B; Table 3).

### 311 *Paleolatitude*

312 Paleolatitudes of eolian systems in this study are subdivided into the following categories: 0-15°, 16-30°, 31-  
313 45°, and 46-60°; the number of case studies falling into these categories are 11, 12, 5, and 4, respectively. A  
314 statistically significant difference is seen between icehouse and greenhouse eolian architectural element  
315 thicknesses for both paleolatitude ranges of 0-15° and 16-30° (Table 3). The mean thickness of eolian  
316 architectural elements deposited in paleolatitudes of 0-15° are 2.60 m and 6.38 m for icehouse and greenhouse  
317 systems, respectively (Fig. 8C, 9). The mean thickness of eolian architectural elements deposited in  
318 paleolatitudes of 16-30° are 2.72 m and 6.40 m for icehouse and greenhouse systems, respectively (Fig. 8C,  
319 9). However, for systems from paleolatitudes >30°, no statistically significant difference is seen in mean eolian  
320 architectural element thickness (Table 3).

### 321 *Dune-Field (Erg) Physiographic Setting*

322 Major sand seas (ergs) can be subdivided into three generalized environmental sub-components: back-,  
323 central- and fore-erg (*sensu* Porter, 1986); the number of case studies falling into these categories are 8, 10,  
324 and 4, respectively. When these three dune-field settings are separately analyzed, a statistically significant  
325 difference in mean eolian architectural element thickness is observed in each erg-setting between icehouse  
326 and greenhouse conditions (Table 3). Back-erg settings record mean eolian architectural element thicknesses  
327 of 1.65 m and 2.92 m for icehouse and greenhouse conditions, respectively (Fig. 8D). Central-erg settings  
328 record mean eolian architectural element thicknesses of 3.39 and 12.83 m for icehouse and greenhouse  
329 conditions, respectively (Fig. 8D). Fore-erg settings record mean eolian architectural element thicknesses of  
330 1.87 m and 6.36 m for icehouse and greenhouse conditions, respectively (Fig. 8D).

## 331 **DISCUSSION**

332 Prevailing climatic conditions influence the caliber of sediment and the rate of its supply, sediment availability  
333 for eolian transport, water-table fluctuations, and wind regimes (variability and strength), all of which  
334 themselves control resultant eolian sedimentary architecture (Kocurek, 1998; Clarke and Rendell, 1998;  
335 Mountney et al., 1999; Nichols, 2005). The observed differences in preserved eolian-element thickness are  
336 interpreted to arise from the prevailing climatic conditions associated with icehouse and greenhouse worlds.  
337 The relative thicknesses of eolian successions are also dependent on the availability of accommodation, and  
338 the rate at which it is created whilst a system is active. Different basin-types are associated with variable rates  
339 of accommodation generation (Gregory, 1894; Rosendahl, 1987; Middleton, 1989; Schlische, 1993; Einsele,  
340 2013); the effects of basin type and accommodation is discussed in section '*Basin Configuration*' below.

### 341 **Icehouse Conditions**

342 When dune sets, sandsheets and interdunes are considered, all are significantly thinner in successions  
343 accumulated under icehouse conditions, relative to those relating to greenhouse conditions. Icehouse  
344 conditions are associated with orbitally controlled oscillations (Milankovitch cycles: Milankovitch, 1941;  
345 Wanless and Shepard, 1936; Dickinson et al., 1994) between drier and windier glacials, favoring eolian-dune  
346 construction (Loope, 1985; Mountney, 2006) – and more humid interglacials, favoring dune deflation (Rea  
347 and Janeck, 1981; Hovan et al., 1991; Petit et al., 1991; Kocurek, 1999; Kocurek and Lancaster, 1999;  
348 Winckler et al., 2008; Woodard et al., 2011). The observation of consistently thinner eolian deposits in the  
349 icehouse stratigraphic record, relative to their greenhouse counterparts, is attributed to the interactions between  
350 these constructive and destructive phases, which operate on timescales of ca. 100-400 kyr (Wanless and  
351 Shepard, 1936; Loope, 1985; Dickinson et al., 1994).

### 352 ***A Sequence of Eolian Accumulation and Deflation***

353 Eolian accumulation and deflation during icehouse times can be described as follows. Globally, shifts from  
354 interglacial to glacial periods tend to be associated with the establishment of more arid conditions, an increase  
355 in wind speeds at trade-wind latitudes, and a relative fall in the level of regional water tables (Figs. 2, 10A;  
356 Rea and Janeck, 1981; Hovan et al., 1991; Petit et al., 1991; Winckler et al., 2008; Woodard et al., 2011).  
357 During the initial phase of glacial waxing and associated marine regression (i.e. equivalent to a falling-stage

358 systems tract; Plint and Nummedal, 2000), large volumes of sediment are made available for potential eolian  
359 transport due to the exposure of areas of the continental shelf, and due to water-table falls that favor the eolian  
360 remobilization of continental deposits (Loope, 1985; Kocurek et al., 2001). The combination of an increase in  
361 the availability of sediment for eolian transport and an increase in the potential sand-carrying capacity of the  
362 wind brought about by increased wind velocity promotes an initial phase of eolian system construction and  
363 accumulation (Kocurek, 1999; Kocurek and Lancaster, 1999). At this stage, accumulating eolian systems tend  
364 to be dominated by sandsheets, associated with intermittent high-speed wind conditions (Clemmensen, 1991),  
365 and by relatively thin dune sets, produced by the repeated cannibalization of trains of dunes climbing at  
366 relatively low angles (Fig. 10A; Mountney, 2006). Thus, sandsheets are expected to form a significantly  
367 greater percentage (20% vs 12%) of observed icehouse eolian elements, relative to greenhouse successions.

368 As glacial conditions continue (at a time equivalent to that of the lowstand systems tract; cf. Van Wagoner et  
369 al., 1990), the increasing aridity drives a further lowering of the water table and the progressive loss of  
370 vegetation (in eolian systems deposited after the evolution of vascular land plants). This leads to the exposure  
371 of even larger sediment volumes, which are made available for entrainment and transport by strong trade  
372 winds with high sediment-carrying capacities (Kocurek, 1998). The relative increase in aridity and windiness  
373 controls both the availability of sediment for eolian transport and the transport capacity of the wind (Fig. 2;  
374 cf. Sarnthein 1978; Anton 1983; Mainguet and Chemin 1983; Lancaster 1989, 1990; Kocurek and Lancaster,  
375 1999). Given these conditions, eolian sediment transport (flux) is large. As sand-saturated air decelerates  
376 within a sedimentary basin in which unfilled accommodation is available, large volumes of sand may be  
377 deposited rapidly; this promotes the accumulation of thicker dune-sets, relative to those deposited at the onset  
378 of an eolian accumulation episode (Fig. 10B; Wilson, 1971, 1973; Middleton and Southard, 1984; Kocurek,  
379 1991; Mountney, 2006). However, the ultimate preservation potential of these thicker dune-sets may be  
380 relatively limited (see below).

381 As a glacial episode continues further, the upwind supply of sand is eventually exhausted (Loope, 1985;  
382 Mountney, 2006). An upwind exhaustion of the sediment supply results in the under-saturation of the airflow  
383 with respect to its potential sand-carrying capacity. This, in combination with the highly erosive trade winds

384 (which can be up to 60% more erosive than they are under greenhouse conditions; Fig. 2; Kidder and Worsley,  
385 2010, 2012) causes a switch to net deflationary conditions around a time of maximum aridity when water  
386 tables are low (Fig. 10C; Loope, 1985; Rubin and Hunter, 1982; Kocurek and Havholm, 1993; Kocurek,  
387 1999). Erosional conditions result in the commencement of erg deflation and destruction (Wilson, 1973; Pye  
388 and Lancaster, 2009; Mountney, 2006; Bállico et al., 2017).

389 During the initial phase of glacial waning and associated onset of marine transgression, eolian deflation of the  
390 dune-sets comprising the uppermost units of an accumulated eolian succession continues (Fig. 10D; timing  
391 equivalent to that of the transgressive systems tract; cf. Van Wagoner et al., 1990). The onset of interglacial  
392 conditions is associated with a relative rise in sea level, a rise in the water table and re-colonization of the  
393 accumulation surface by vegetation. Cumulatively, these factors, in combination with weakened trade-wind  
394 strengths, reduce the volume of sediment susceptible to deflation, and the sediment transport capacity of the  
395 wind (Kocurek, 1991; Mountney, 2006). Water tables rise above the level of the thin dune sets and sandsheet  
396 deposits forming the lower parts of glacial eolian successions (Fig. 10D), thereby enhancing their long-term  
397 preservation potential.

398 As the interglacial proceeds (timing equivalent to that of the highstand systems tract; cf. Van Wagoner et al.,  
399 1990), the strength of trade winds continues to decrease (Fig. 2). The overall reduction in both sediment-  
400 transport capacity and sediment supply rates make interglacial eolian systems both supply- and transport-  
401 limited (cf. Kocurek and Lancaster, 1999). Deflation progresses to the level of the water table (Stokes, 1968),  
402 generating a supersurface (equivalent to a sequence boundary; cf. Van Wagoner et al., 1990), potentially  
403 associated with surface stabilization resulting from colonization by vegetation or microbial communities, by  
404 chemical precipitates, or by fluvial inundation (Fig. 10D; Loope, 1988; Kocurek, 1991; Dott, 2003; Basilici  
405 et al., 2009, 2020; Eriksson et al., 2000; Dal' Bo et al., 2010; Simpson et al., 2013). The timing of eolian  
406 supersurface formation can span a protracted length of time, and its culmination can vary in timing from late  
407 in a glacial episode to a point of maximum humidity during an ensuing interglacial episode (i.e. associated  
408 with the highstand systems tract). Thus, the timing of supersurface formation may contrast with that of

409 sequence boundary formation in marine environments, which typically occurs during the falling-stage and  
410 early lowstand systems tracts (cf. Mitchum, 1977).

411 As the interglacial continues, eolian accumulation remains limited. This is due to the cumulative effects of  
412 elevated water tables and increased vegetation cover (in eolian systems deposited after the evolution of  
413 vascular land plants), which act to limit sediment availability (Fryberger et al., 1990; Kocurek and Havholm,  
414 1993; Kidder and Worsley, 2010), and weaker wind strengths, which act to limit sediment transport capacity  
415 (Kocurek, 1999). This cycle of eolian accumulation recommences when climatic conditions tip back into  
416 windier, more arid glacial conditions (Fig. 10E-G).

417 The process of deflation preferentially erodes the larger dune sets occurring in the upper part of eolian  
418 successions that accumulated during glacial episodes; the thinner dune-sets and sandsheets forming the lower  
419 parts of such successions are less prone to deflation, since the concomitant rise in the water table can lead to  
420 their permanent preservation in the stratigraphic record (Fig. 10D; Kocurek and Havholm, 1993; Mountney  
421 and Russell, 2009; Mountney 2006). The preservation of relatively thicker dune-sets, associated with peak  
422 aridity during glacial times, may be limited to times and tectonic contexts of rapid subsidence. On the basis  
423 of this evolutionary model, the significantly reduced thickness of icehouse – relative to greenhouse – eolian  
424 architectural elements (i.e. dune-sets, sandsheets and interdunes) in the geological record is explained by their  
425 reduced preservation potential over Milankovitch timescales (100-400 kyr).

### 426 *Icehouse Deflation*

427 During icehouse glacial episodes, generally more arid landscapes are associated with relatively depressed  
428 water tables. As such, accumulating eolian successions are less likely to be permanently sequestered beneath  
429 the water table, and are therefore prone to deflation by strengthened low-latitude trade winds (Kocurek and  
430 Havholm, 1993). Such episodes are also generally associated with a reduced presence of stabilizing agents on  
431 the Earth's surface (e.g., vegetation and biogenic and evaporitic crusts), leaving eolian deposits exposed to  
432 potential erosion (Loope, 1988; Kocurek, 1991; Basilici et al., 2009, 2020; Dal' Bo et al., 2010).

433 The propensity of icehouse conditions to drive significant wind erosion following the cessation of eolian  
434 accumulation is supported by the dominance of deflationary supersurfaces, which are more common under

435 icehouse conditions, relative to greenhouse conditions (deflationary supersurfaces represent 88% and 67% of  
436 classified supersurfaces in icehouse and greenhouse systems, respectively). The formation of deflationary  
437 supersurfaces with associated wet-surface features indicates that conditions of net accumulation are related to  
438 cyclic changes to net-erosional conditions, associated with eolian cannibalization and deflation down to the  
439 water table (Stokes, 1968; Loope, 1985; Mountney and Jagger, 2004; Mountney, 2006). This is the case for  
440 the icehouse Cedar Mesa Sandstone and many other Permo-Carboniferous deposits across North America, in  
441 which erg sequences are capped by regionally extensive deflationary, supersurfaces with associated  
442 sedimentary structures that indicate deflation to the paleo-water table (Loope, 1985; Fryberger, 1993;  
443 Mountney and Jagger, 2004; Mountney, 2006).

444 Greater rates of eolian winnowing under icehouse conditions are indicated by the higher number of  
445 observations of sandsheet elements. Sandsheets can represent remnants of eroded landforms of originally  
446 higher relief; their occurrence can reflect eolian deflation, whereby the winnowing of finer-grained sand leaves  
447 behind a coarser lag (Nielsen and Kocurek, 1986; Pye and Tsoar, 1990; Mountney and Russell, 2004, 2006).  
448 It is therefore significant that deflationary lag strata form a common facies type in icehouse sandsheet deposits,  
449 but are a comparatively rare component of greenhouse sandsheet deposits. The evidence of heightened eolian  
450 deflation of sandsheets accumulated under icehouse conditions suggests that in this global climate regime the  
451 cannibalization of eolian deposits was more common, in accord with the preservation of relatively thinner  
452 eolian architectural elements (dune sets, sandsheets, interdunes). The preferential cannibalization of eolian  
453 systems under icehouse conditions indicates a propensity for these systems to develop a negative sediment  
454 budget (likely due to exhaustion of an upwind eolian sediment supply).

455 The greater propensity for icehouse eolian systems to experience post-depositional deflation is supported by  
456 the textural analysis of icehouse and greenhouse deposits. Overall, analysis of sediment textures reveals that  
457 icehouse deposits are less texturally mature, have higher mean values of modal grain sizes, are relatively more  
458 poorly sorted, and have grains that are significantly more angular. The reduced textural maturity of icehouse  
459 sediments may be attributed to the relatively coarse and angular nature of grains that constitute a winnowed  
460 lag left being during the development of sandsheet elements (Nielsen and Kocurek, 1986; Pye and Tsoar,

1990; Mountney and Russell, 2004, 2006). However, the differences in grain size and sorting are not sufficiently large to be considered statistically significant; this finding is congruous with the highly discriminant nature of sediment transport by wind (Bagnold, 1941), which may generate a relatively well-sorted sediment source prior to deflation.

### **Greenhouse Conditions**

The fact that dune-set, sandsheet and interdune architectural elements are significantly thicker in successions accumulated under greenhouse conditions, relative to those relating to icehouse conditions (Fig. 4) is attributed to their greater preservation potential over 100-400 kyr timescales. Relative to icehouse conditions, greenhouse Earth provides favorable conditions for the rapid incorporation of eolian elements into the geological record. Greenhouse conditions are associated with high eustatic levels and more-humid conditions, which generally promote elevated water tables situated close to the accumulation surface (Kocurek et al., 2001; Cowling, 2016).

Although the greenhouse geological record testifies to temporal variations in humidity (e.g., Sames et al., 2020), the greenhouse Earth did not generally experience large-magnitude shifts in global climate, relative to the glacial-interglacial oscillations of icehouse periods. As such, greenhouse conditions are generally associated with consistently elevated water tables, which experience only minor temporal changes in elevation relative to the accumulation surface (Fig. 11). Consistently elevated water tables can effectively sequester eolian successions; accumulating eolian successions are rapidly buried beneath the level of the water table, in response to progressive but gradual subsidence, and are accordingly protected from potential deflation by the wind, leading to the long-term accumulation of eolian systems (Fig. 11; Kocurek and Havholm, 1993; Mountney and Russell, 2009). Elevated water-table conditions are supported by the greater proportion of ‘wet’ interdune and ‘sabkha’ elements in greenhouse eolian successions (Evans, et al., 1964; Purser and Evans, 1973; Fryberger et al., 1990; Kocurek and Havholm, 1993; Garcia-Hidalgo, 2002).

Elevated water tables interact with the accumulation surface to generate damp and wet substrates that inhibit the deflation of eolian sand deposits; greater threshold velocities are required to entrain wet or damp sand due to capillary water tension (Chepil, 1956; Bisal and Hsieh, 1966; Azizov, 1977). Humid, shallow water-table

487 conditions may also promote the colonization of eolian substrates by vegetation or biogenic films or crusts in  
488 some paleoenvironmental settings (Basilici et al., 2020). Vegetation can limit the mobility of channelized river  
489 systems, which can potentially erode contiguous adjacent eolian deposits (Davies and Gibling, 2010; Reis et  
490 al., 2020; Santos et al., 2017, 2020). Moreover, vegetation can play a crucial role in dune construction and  
491 stabilization; vegetation disrupts primary airflows in the near-surface layer, decelerating winds and leading to  
492 the fall-out from the airflow of airborne sand grains (Kocurek and Nielsen, 1986), thereby promoting  
493 deposition; once deposited, vegetation can effectively trap eolian sediment, protecting it from re-suspension  
494 and potential erosion (Byrne and McCann, 1990; Ruz and Allard, 1994). The precipitation of early diagenetic  
495 cements around plant-root structures in eolian sand can further stabilize eolian surfaces (Mountney 2006).

496 The role of vegetation is only relevant for icehouse and greenhouse systems deposited after ca. 420 Ma, when  
497 vascular land plants became widespread (Gifford and Foster, 1989; Rainbird, 1992; Long, 2006; Davies and  
498 Gibling, 2010). However, the statistically significant difference in mean eolian architectural element thickness  
499 for icehouse and greenhouse conditions is also present in pre-vegetation Precambrian settings (see section  
500 *'Precambrian Supercontinent'*). It can therefore be inferred that vegetation may play a contributing, but not  
501 crucial, role in determining eolian element thickness. Prior to the evolution of land plants, other biotic  
502 stabilizing agents likely played a role in limiting eolian winnowing, notably the presence of microbial films  
503 and crusts (e.g., Basilici et al., 2020).

504 The inference of the role played by stabilizing agents and higher water tables in minimizing eolian deflation  
505 is supported by the nature of supersurfaces seen in greenhouse systems, which are less likely to be deflationary  
506 than those formed under icehouse conditions (Fig. 7A). Greenhouse supersurfaces may be more likely to  
507 develop due to changes in depositional environment, such as fluvial inundation (Fig. 11), or the development  
508 of sabkha elements. The close proximity of the water table to the surface is interpreted to result in more closely  
509 spaced supersurfaces in greenhouse eolian successions.

## 510 **Non-Eolian Elements**

511 Non-eolian elements, which interdigitate with eolian elements to varying degrees, and which form over a third  
512 of all recorded element types by number of occurrences (comprising 37% and 38% of icehouse and greenhouse

513 successions, respectively) in otherwise eolian-dominated successions, do not show a statistically significant  
514 difference in mean thickness between icehouse and greenhouse conditions. This might indicate that, within  
515 dominantly eolian systems, the thicknesses of interdigitated non-eolian elements are not primarily controlled  
516 by factors that are inherent to icehouse and greenhouse climatic conditions. This supports the idea that  
517 variations in eolian element thicknesses noted between icehouse and greenhouse systems are largely due to  
518 the effects of changes in wind strength as a driver of eolian accumulation and deflation. Many non-eolian  
519 elements are associated, to varying degrees, with deposition in aqueous environments and are therefore  
520 unaffected or slightly affected by changes in wind speed, strength and erosive power.

## 521 **Other Boundary Conditions**

### 522 *Supercontinental Setting*

523 The paleogeographic configuration and distribution of land masses has influenced sea level, global  
524 temperatures and patterns of atmospheric circulation. Only two paleogeographic states have existed in Earth  
525 history that spanned both icehouse and greenhouse conditions: the Precambrian and Pangean supercontinental  
526 configurations. When icehouse and greenhouse conditions are separately compared for these two  
527 supercontinental settings, the same statistical differences in eolian element thicknesses persist, such that eolian  
528 deposits associated with icehouse conditions are significantly thinner than those associated with greenhouse  
529 conditions. This suggests that the prevailing global climate regime may have influenced the development and  
530 preservation of eolian systems across different supercontinental configurations. The Precambrian and Pangean  
531 supercontinents are considered below.

532 *Precambrian Supercontinents* Evidence of Precambrian glaciogenic deposits have been recorded  
533 from many continental land masses, including those originally placed at tropical paleolatitudes (Shrag, 2002;  
534 Kirschvink, 1992). Precambrian icehouse conditions are attributed to attenuated solar luminosity, the albedo  
535 caused by continental landmasses located at low-latitudes, and relatively low levels of atmospheric carbon  
536 dioxide (Hoffman et al., 1998; Kirschvink, 1992).

537 In rocks of Precambrian age, icehouse eolian deposits are significantly thinner relative to their greenhouse  
538 counterparts (Fig. 8A). Changes in the strength and erosive power of the trade winds are likely equally relevant

539 for eolian deposits of Precambrian age, as Hadley cell circulation is shown to have been active since the  
540 Proterozoic (Hoffman and Grotzinger, 1993). As such, the greater strength and erosive power of icehouse  
541 winds (Fig. 2) may be responsible for enhanced winnowing and deflation of Precambrian icehouse eolian  
542 architectural elements. Precambrian icehouse conditions are considered to have been amongst the most  
543 extreme of all recorded icehouse periods; wind strength and erosive power are interpreted to have been  
544 amongst the highest in Earth history (Fig. 2; Kirschvink, 1992; Allen and Hoffman, 2005).

545 Several of the studied Precambrian successions are associated with deposition in intracratonic basins, which  
546 are preferentially developed in the interiors of stable ancient cratons (e.g., Shaw et al., 1991; Aspler and  
547 Chiarenzelli, 1997; Deb and Pal, 2015), and which act as sites where relatively thin eolian elements can  
548 accumulate and be preserved, through episodic deposition between long periods of sediment bypass,  
549 controlled in part by relatively slow rates of subsidence and accommodation generation (e.g., Bethke, 1985;  
550 Aspler and Chiarenzelli, 1997). However, the differences in eolian element thickness between icehouse and  
551 greenhouse successions cannot be ascribed to the basin setting that hosts them (Fig. 12). In this study,  
552 greenhouse Precambrian deposits are all associated with accumulation in intracratonic basins, however, their  
553 icehouse counterparts are largely associated with deposition in continental rift and peripheral foreland basin  
554 settings; Fig. 12). Even though a bias in this study exists whereby the studied Precambrian greenhouse eolian  
555 deposits were all deposited in slowly subsiding intracratonic basins, the elements that make up these deposits  
556 are still significantly thicker than their Precambrian icehouse counterparts (Fig. 8A). This suggests that the  
557 climatic influence on eolian element thickness overrides the potential control on preservation of  
558 accommodation generation and basin morphology.

559 ***Pangean Supercontinent*** The Late Paleozoic is associated with a transition from icehouse to  
560 greenhouse conditions and changes in global atmospheric circulation (e.g., Rowley et al., 1985; Cecil, 1990;  
561 Parrish, 1993; West et al., 1997; Gibbs et al., 2002). The Late Paleozoic global climate change was closely  
562 associated with the formation of the Pangean supercontinent. The assemblage of Pangea resulted in the  
563 aggregation of large volumes of continental landmasses centered on the South Pole (Smith et al., 1973;  
564 McElhinny et al., 1981; Ziegler et al., 1983), which experienced widespread continental glaciation from ca.

565 360 to 300 Ma. The spread of continental glaciation was halted by increasing levels of atmospheric carbon  
566 dioxide and the northward drift of the continents: after ca. 300 Ma, the Earth tipped back into greenhouse  
567 climatic conditions (Parrish, 1993). The Pangean supercontinent disrupted zonal atmospheric circulation,  
568 leading to the development of the Pangean megamonsoon, which is comparable to the East Asian Monsoon  
569 and was characterized by a seasonal reversal of winds (Kutzbach and Gallimore, 1989; Parrish, 1993). The  
570 megamonsoon was active in the Permian, intensified into the Triassic, and continued on the Gondwanan  
571 supercontinent until the beginning of the Cretaceous (Parrish, 1993; Scherer and Goldberg, 2007; Scherer et  
572 al., 2020).

573 The megamonsoon and its associated seasonal reversals in wind direction are widely documented in the eolian  
574 record and have likely influenced the architecture of eolian deposits (e.g., Loope et al., 2001). It can thus be  
575 hypothesized that the megamonsoon may have also governed accumulated eolian element thickness, perhaps  
576 in a way that would have overprinted the effects of the controls exerted by icehouse and greenhouse conditions.  
577 However, despite the additional control imposed by megamonsoon conditions, icehouse eolian architectural  
578 elements (i.e. dune-sets, sandsheets and interdunes) remain significantly thinner than greenhouse architectural  
579 elements in stratigraphies of this age (Fig. 8A). Moreover, the mean thickness of greenhouse Pangean  
580 architectural elements (i.e. those deposited under peak megamonsoon conditions) does not differ significantly  
581 from greenhouse architectural elements deposited under comparable supercontinental settings (Fig. 13; Table  
582 3). The impact of the megamonsoon on accumulated eolian element thickness is therefore considered to have  
583 been secondary compared to the climatic influence of icehouse-greenhouse oscillations. However, a limitation  
584 exists in this analysis, since icehouse conditions only prevailed on Pangea during its initial accretion, and the  
585 Pangean climate was dominated by greenhouse conditions for the majority of its existence.

### 586 ***Basin Configuration***

587 The long-term preservation of eolian systems in the geological record requires the development of  
588 accommodation in which eolian deposits can accumulate. The basin morphology and rate of accommodation  
589 generation varies significantly between the basin types considered here (intracratonic, rift and foreland basins;  
590 see Table 2). Despite this, statistical differences between the thicknesses of icehouse and greenhouse

591 architectural elements are noted for all basin types considered in this study (Fig. 8B), whereby eolian  
592 architectural elements associated with icehouse periods are significantly thinner than those of greenhouse  
593 periods. This suggests that the climatic influence on eolian element thickness overrides the potential controls  
594 of accommodation generation and basin morphology.

### 595 *Paleolatitude*

596 The preserved architecture of eolian systems is influenced by the latitude at which the eolian systems  
597 developed (Fig. 8C). The existence of the icehouse/greenhouse signature at low latitudes ( $<30^\circ$ ), and the  
598 absence of this signature at higher latitudes ( $>30^\circ$ ), supports the previous assertion that the differences in  
599 eolian element thicknesses are governed by atmospheric circulation at low latitudes, caused by  
600 icehouse/greenhouse modulation of the Hadley circulation, and associated with changes in the strength of the  
601 trade winds (Chandler, 1992; Lu et al., 2007; Hasegawa et al., 2011). Outside the zone of influence of the  
602 trade winds ( $>30^\circ$  latitude), the icehouse-greenhouse signature is apparently not evident in the geological  
603 record; this suggests that the effects of global climate oscillations are overprinted by other forcing mechanisms  
604 in that context, such as rate and type of sediment supply, tectonic configuration, basin setting and dune-field  
605 physiographic setting.

### 606 *Dune-field (Erg) Physiographic Setting*

607 Across the different dune-field settings of eolian sand seas (i.e. back, center and fore erg-settings), variations  
608 in eolian element thickness are seen, with central-erg eolian architectural-elements being on average thicker  
609 than fore- and back-erg elements. However, across all environments of eolian sand seas, statistically  
610 significant differences in eolian architectural element thickness are seen between icehouse and greenhouse  
611 successions, such that icehouse eolian elements are consistently thinner relative to greenhouse architectural  
612 elements (Fig. 8D). The fact that this difference is seen across all dune-field physiographic settings  
613 corroborates the idea that the differences in eolian element thickness are the result of large-scale circulation  
614 patterns, which overprint signatures associated with localized and autogenic controls.

## 615 **CONCLUSIONS**

616 The continental terrestrial record has here been shown to preserve a valuable archive of how ancient  
617 sedimentary systems respond to and record changes in global climate. This study provides the first integrated  
618 global-scale quantitative investigation into the effects of climatic oscillations on eolian sedimentary  
619 architecture. More than >5,600 geological entities extracted from 34 case studies, spanning a variety of spatio-  
620 temporal settings, have been analyzed (Fig. 1). Icehouse and greenhouse conditions exert a fundamental and  
621 statistically detectable influence on preserved eolian dune-set, sandsheet and interdune thicknesses (Fig. 4;  
622 Table 3), such that icehouse eolian architectural elements are significantly thinner than greenhouse  
623 architectural elements. This statistical signature is present regardless of (i) basin type, (ii) paleogeographic  
624 configuration, and (iii) dune-field (erg) physiographic setting (Fig. 8; Table 3). However, the icehouse-  
625 greenhouse signature is only present at paleolatitudes <30°; it is absent in systems from higher paleolatitudes  
626 (Fig. 8C). Differences in eolian element thicknesses are interpreted in terms of changes in the pattern of  
627 circulation of low-latitude trade winds (Fig. 2), which operate at latitudes <30°.

628 Under icehouse conditions, Milankovitch-driven cycles of eolian accumulation and deflation result in the  
629 preservation of thin eolian architectural elements (i.e. dune sets, sandsheets and interdunes Figs. 4, 10); as an  
630 icehouse glacial initiates, thin dune sets and sandsheets are deposited under high wind strengths. As the glacial  
631 proceeds, higher trade-wind strengths result in the deposition of relatively thicker dune-sets, until upwind  
632 sources are exhausted (Fig. 10). The thick glacial dune-sets have limited preservation potential due to  
633 depressed water tables and the highly erosive nature of the strengthened trade winds. During interglacial  
634 periods, relative rises in the water-table enable the preservation of the thin basal dune-sets and sandsheets  
635 (Fig. 10).

636 Relative to greenhouse conditions, icehouse conditions are also associated with (i) a greater proportion of  
637 deflation-lag facies in sandsheet and interdune elements; (ii) relatively more observations of sandsheet strata,  
638 indicative of higher wind strengths; and (iii) a higher proportion of deflationary supersurfaces (Fig. 7).  
639 Consistently and significantly thicker greenhouse deposits are attributed to relatively elevated water tables  
640 (associated with wet interdunes and sabkha elements), which exhibit only minor temporal variations in level  
641 relative to the accumulation surface, and enhanced surface stabilization by vegetation or other biotic agents,

642 all of which inhibit eolian deflation. Relative to icehouse conditions, greenhouse conditions are associated  
643 with: (i) eolian architectures dominated by an increased occurrence of dune-set elements, with fewer recorded  
644 sandsheet and interdune elements (Fig. 3B); (ii) interdunes that, where present, are more likely to be of a damp  
645 or wet type (Fig. 5A); (iii) a greater proportion of interdigitating sabkha elements (Fig. 3C).

646 This study presents a quantitative assessment of how the influence of icehouse and greenhouse climates on  
647 Earth surface processes is archived in the continental stratigraphic record. The results presented here provide  
648 novel insights into the fundamental boundary conditions that govern eolian sedimentary architectures, and  
649 have been used to develop idealized eolian icehouse and greenhouse facies models based on the most likely  
650 association of eolian and associated non-eolian architectural elements and bounding surfaces. The  
651 architectures of low-latitude eolian systems are fundamentally influenced by the prevailing global climate,  
652 and the way this influence has been translated into the stratigraphic record has been consistent through  
653 geological time. Results presented here help quantify and understand sedimentary responses to fundamental  
654 processes that operate on the surface of the Earth as a consequence of changes in global climate. In the context  
655 of human-induced climate change, these findings may be valuable for future predictions of the response of the  
656 terrestrial geosphere to fundamental changes in global climate.

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583

## 584 **FIGURE CAPTIONS**

585

586 1. A) Distribution of case studies used in this investigation, coloured according to icehouse (blue) and  
587 greenhouse (orange) conditions (this colour scheme applies throughout this account). The shape of the  
588 marker indicates the paleosupercontinental setting of the case study. B) Geological time-scale showing the  
589 five major icehouse periods (labelled A-E) and the distribution of the supercontinents. For all icehouse  
590 case-studies, the marker contains a letter (A-E) denoting the associated icehouse period.

- 591 2. Factors commonly associated with icehouse and greenhouse conditions. Boxes A-E are theoretical. F)  
592 Low latitude sea surface temperatures (based on estimates in Forster et al., 2007). G) Estimates of pCO<sub>2</sub>  
593 (based on values in Shaviv and Veizer, 2003). H) Pole to equator thermal contrast. I) Planetary windbelt  
594 speed ( $V$  = velocity). J) Wind shear ( $V^2$  = wind velocity squared). K) Wind erosive power ( $V^3$  = wind  
595 velocity cubed). Boxes H-K are based on the estimates of Kidder and Worsley (2010); the units for boxes  
596 I-K are expressed as fractions of the maximum (e.g., 0.67 would be 2/3 of the maximum). Figure adapted  
597 in part from Kidder and Worsley (2012).
- 598 3. Percentages of: A) eolian and non-eolian architectural elements, B) dune set, sandsheet and interdune  
599 elements, and C) non-aeolian elements, deposited under icehouse and greenhouse conditions. Percentages  
600 of eolian and non-eolian architectural elements are determined based on total element counts. For  
601 descriptions of eolian and non-eolian architectural element types see Table 2.
- 602 4. Box and whisker plots showing distributions in element thickness for icehouse and greenhouse conditions:  
603 A) all eolian elements; B) dune sets; C) sandsheets; D) interdunes; E) all eolian facies. For descriptions of  
604 eolian architectural element types see Table 2.
- 605 5. Percentages of: A) wet, dry, and damp interdunes; and the distribution of facies in B) interdunes and C)  
606 sandsheets. The percentages are determined based on the total element count. For descriptions of interdune  
607 types and facies element types see Table 2.
- 608 6. Box and whisker plots of icehouse and greenhouse textural properties. A) modal grain-size; B) sorting; C)  
609 grain roundness.
- 610 7. Percentages of supersurface descriptions. A) Bypass and deflation surfaces; B) surface 'wetness'; C)  
611 surface stabilization. Percentages are calculated based on numbers of occurrences in vertical sections. For  
612 full descriptions of surface types and associated attributes see Table 2.
- 613 8. Box and whisker plots of element thickness for elements grouped by: A) Proterozoic and Pangean  
614 paleosupercontinental settings; B) rift, foreland and intracratonic basin settings; for descriptions of basin  
615 types see Table 2; C) different paleolatitudes; and D) different dune-field physiographic settings.
- 616 9. Scatterplot showing values of icehouse and greenhouse eolian element thicknesses for different  
617 paleolatitudes with mean and median overlain.

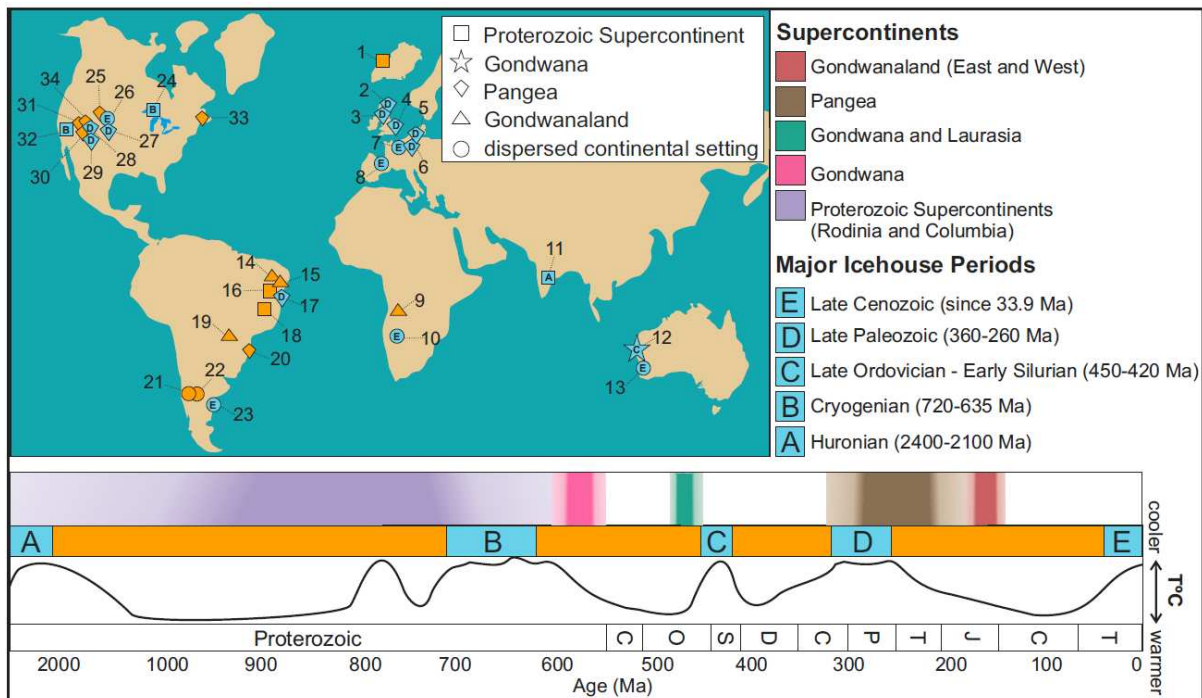
- 618 10. Cycles of eolian accumulation and deflation under icehouse glacials and interglacials with accompanying  
619 sequence stratigraphic terminology. A) Deposition of thin sandsheet and dune-set elements associated with  
620 the onset of glacial conditions. B) Deposition of thick dune sets associated with strong trade-wind strengths  
621 and high rates of sediment supply in an arid setting. Both A and B show a relative fall in the level of the  
622 water table. C) Onset of deflation as a sediment source is exhausted. D) As interglacial conditions proceed,  
623 deflation continues to the level of the water table. Both C and D show a rise in the relative level of the  
624 water table, associated with more humid interglacial conditions. The rise in the level of the water table  
625 protects the lower part of the aeolian succession from erosion. E-G the start of a new glacial/interglacial  
626 cycle. The indicative lateral and vertical scales in Part A apply to all box models.
- 627 11. Deposition of an eolian sequence under greenhouse conditions. The temporal sediment supply remains  
628 relatively static (A-D). An elevated water table associated with relatively humid conditions promotes the  
629 preservation of eolian dune sets by protecting them from potential wind erosion; accumulated dune sets  
630 are sequestered into the geological record (B-D). The generation of supersurfaces is most likely to be  
631 associated with fluvial inundation or due to a transition from eolian to sabkha deposition (C). The  
632 indicative lateral and vertical scales in Part A apply to all box models.
- 633 12. Percentages of different basin-setting types (continental rift, foreland and intracratonic) for Proterozoic  
634 age case studies, subdivided into icehouse and greenhouse conditions.
- 635 13. Box and whisker plots showing eolian architectural element thicknesses for Proterozoic, Pangean and  
636 Gondwanaland paleosupercontinental settings.

## 638 **TABLE CAPTIONS**

- 639
- 640 1. List of the case studies used in this investigation. The geographic location of each case study is outlined  
641 in Figure 1 (identified via the case number). The reference refers to the original source material from which  
642 quantitative metrics were derived.
- 643 2. Definitions of eolian and non-eolian architectural element types, facies element types, surface types, and  
644 basin types discussed in the text.

645 3. Results of statistical analysis; SD: standard deviation; P(T<=t): one tail t-test; ANOVA: analysis of  
 646 variance. All results are reported to two decimal places, where appropriate. For all statistical calculations  
 647 see Supplementary Information.

648 Figure 1



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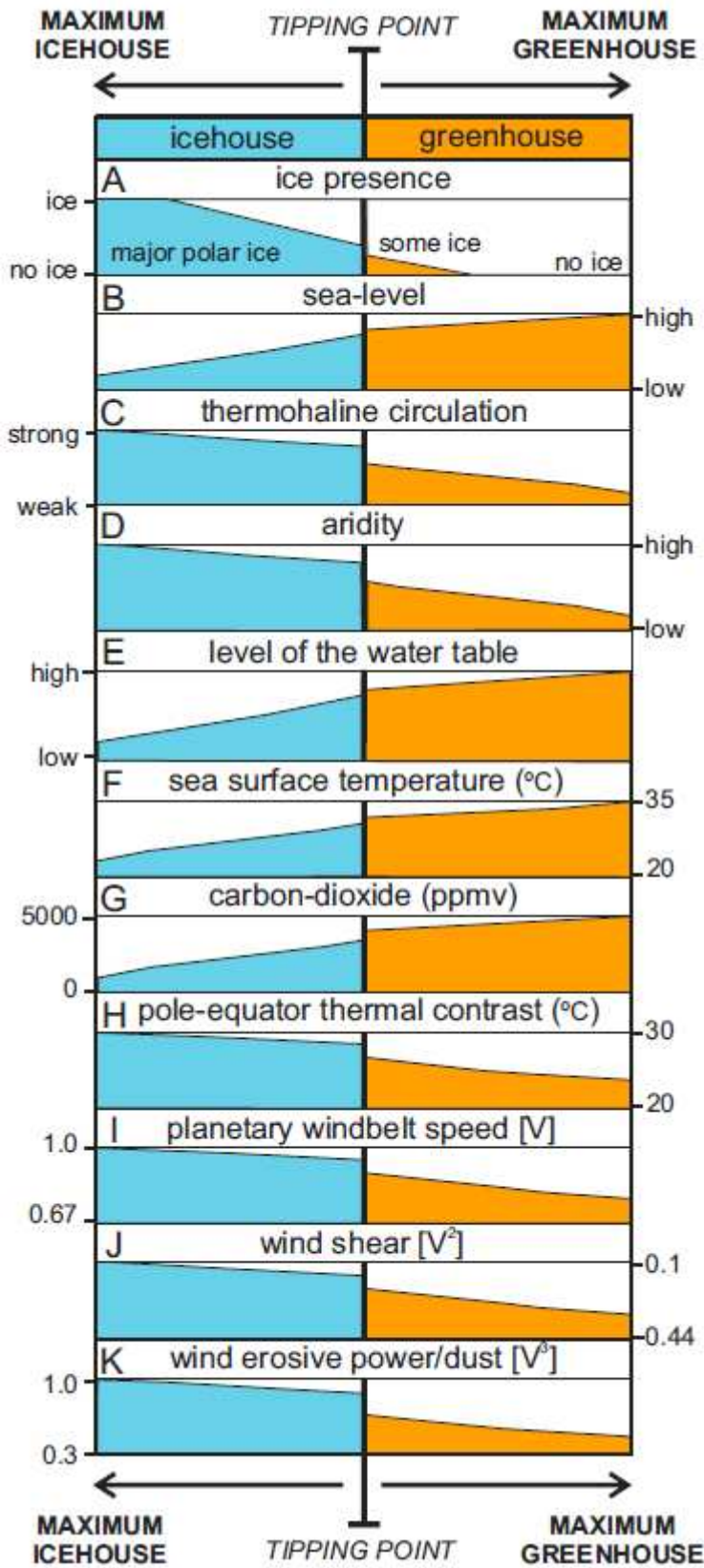
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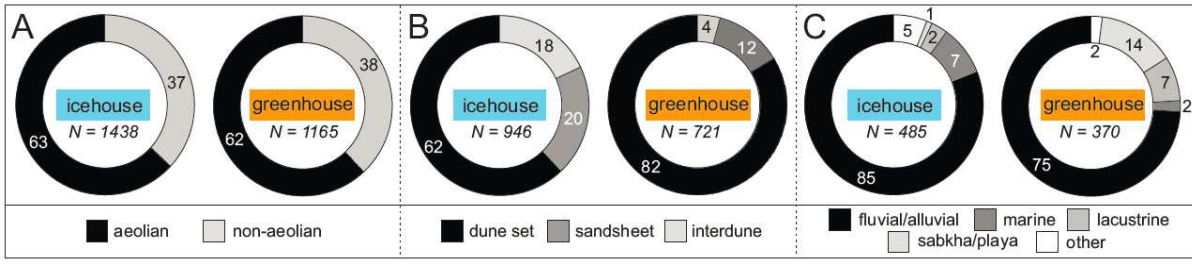
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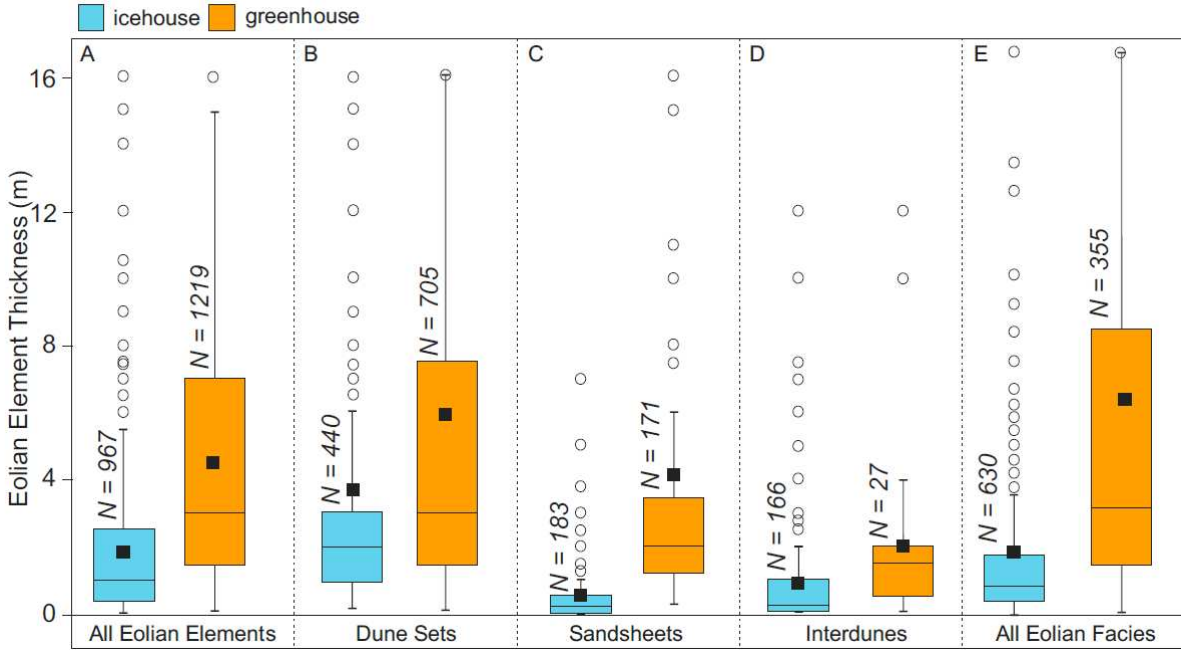
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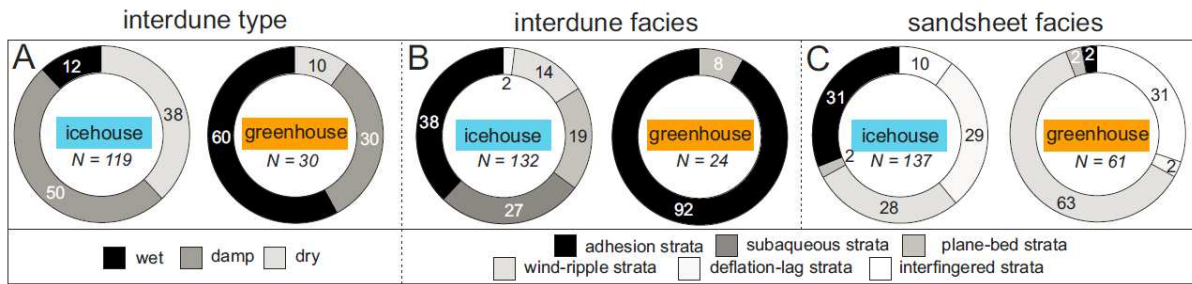
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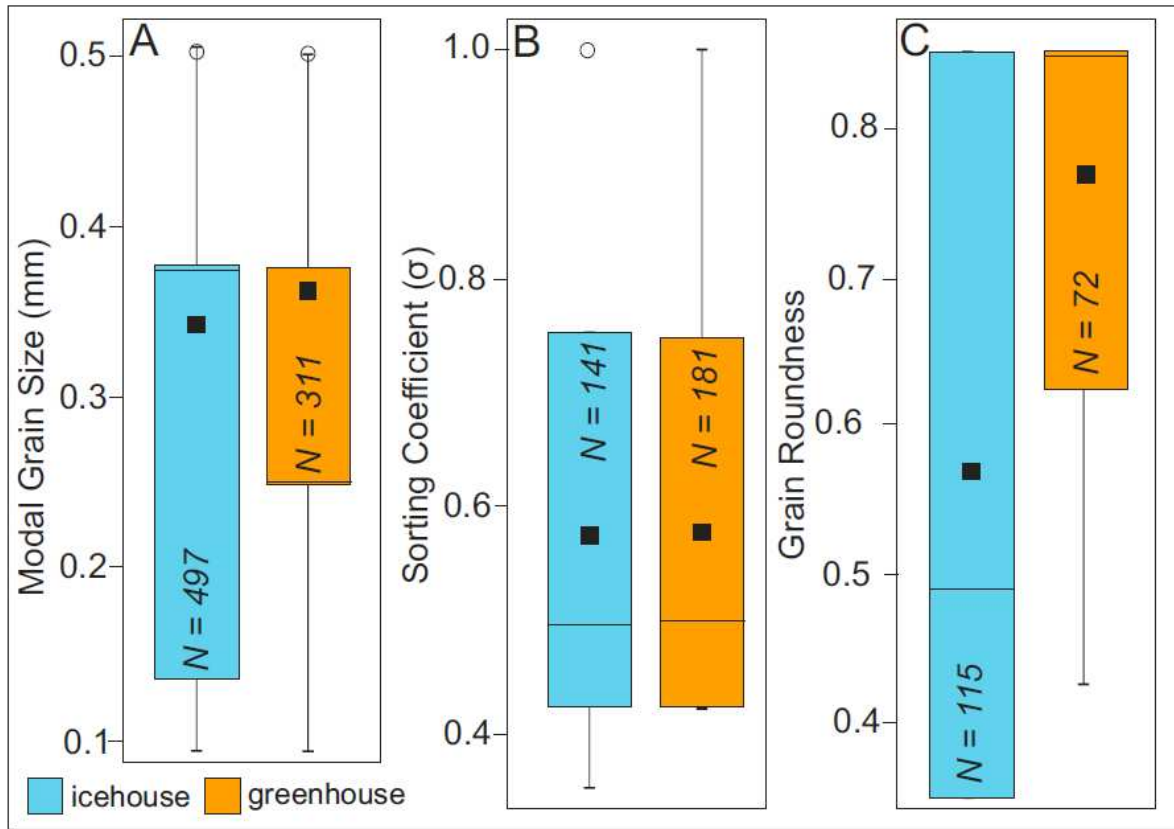


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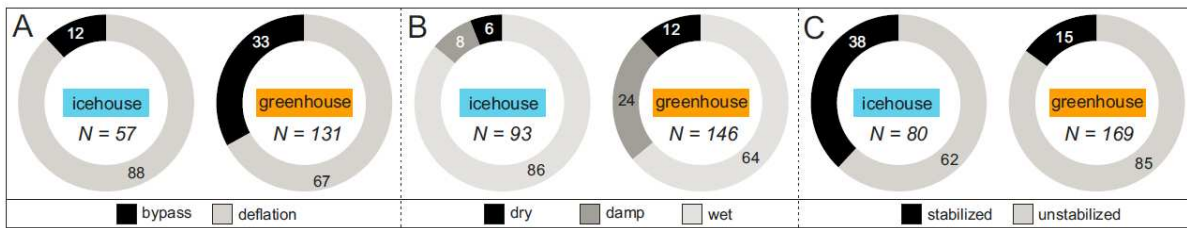
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693 Figure 7



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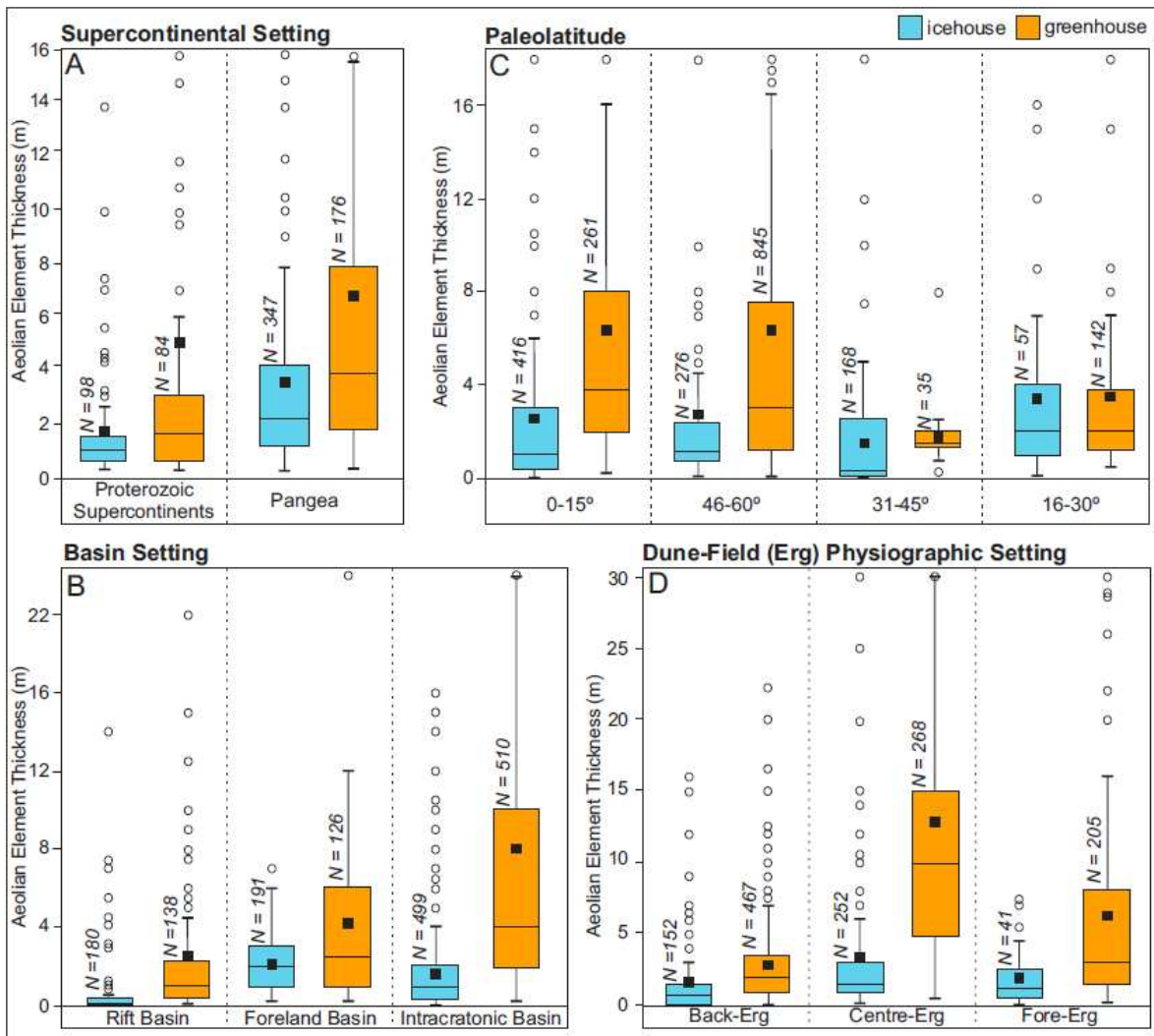
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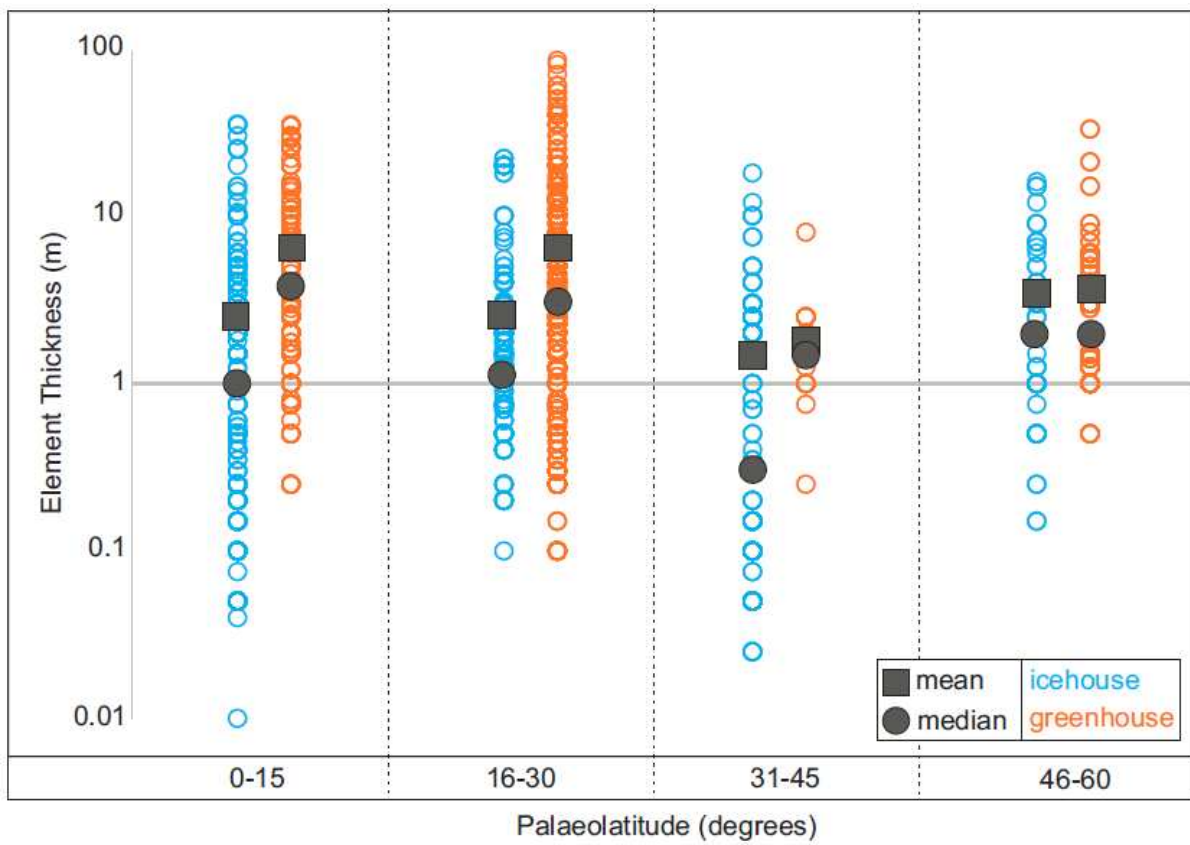
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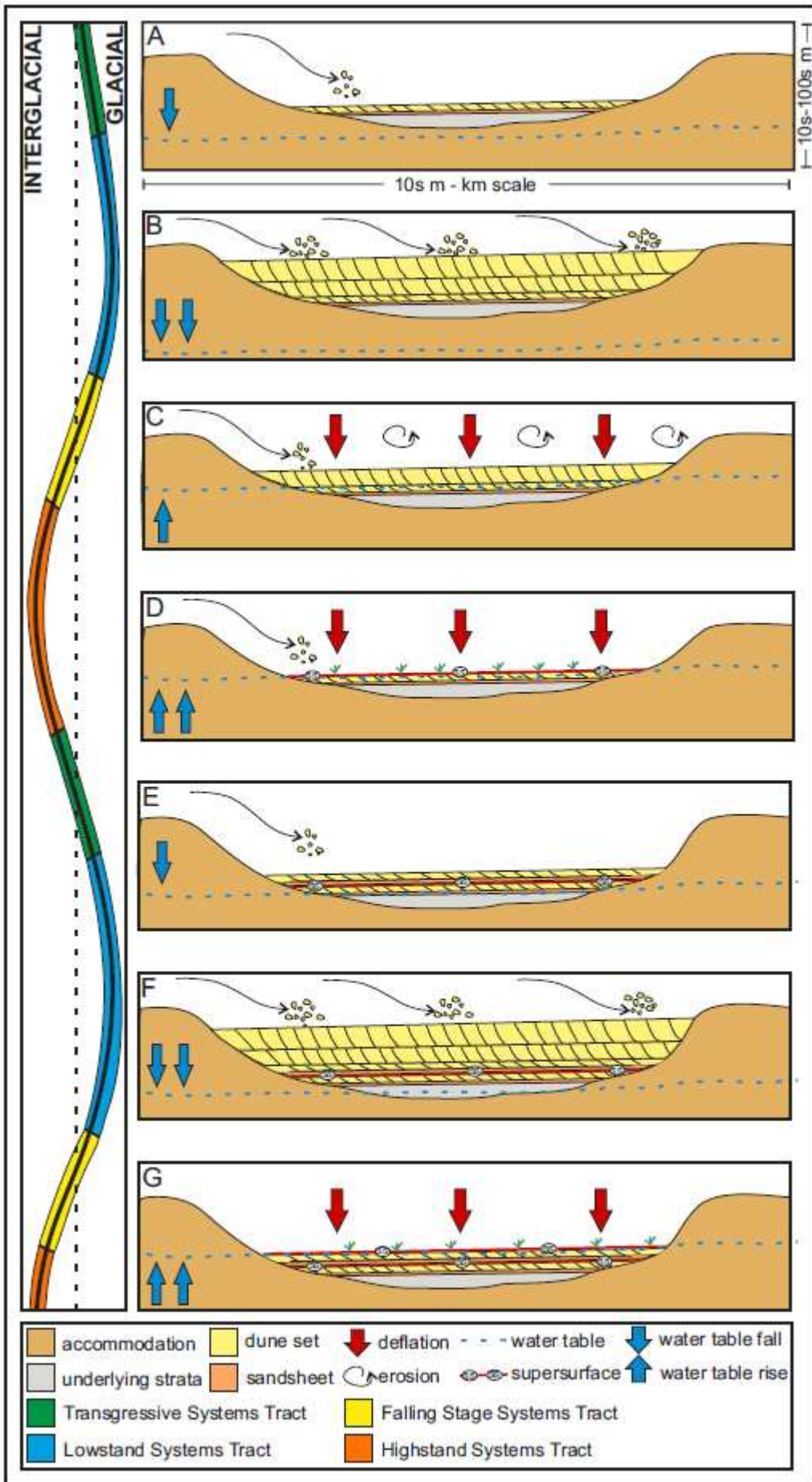
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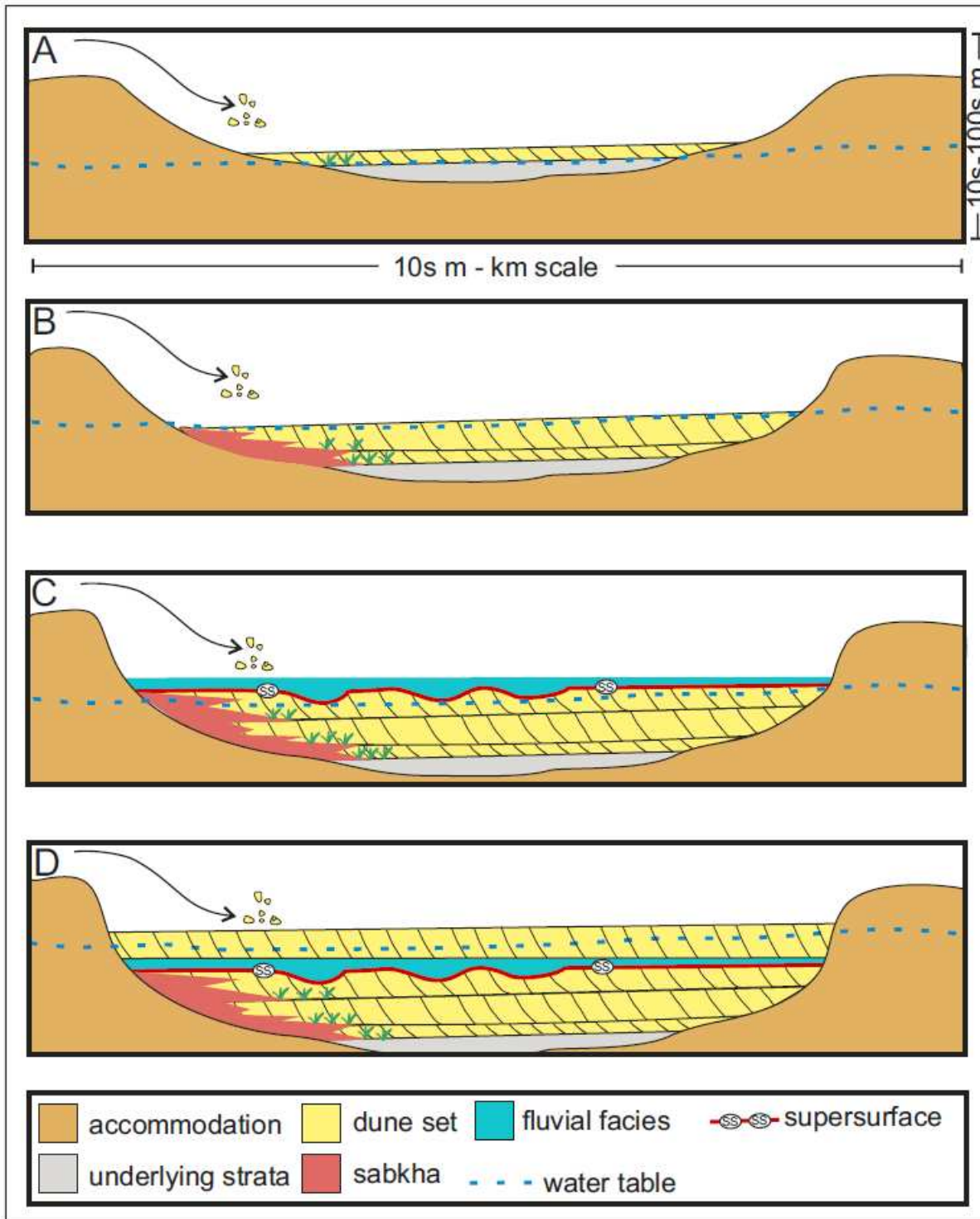


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752 Figure 11



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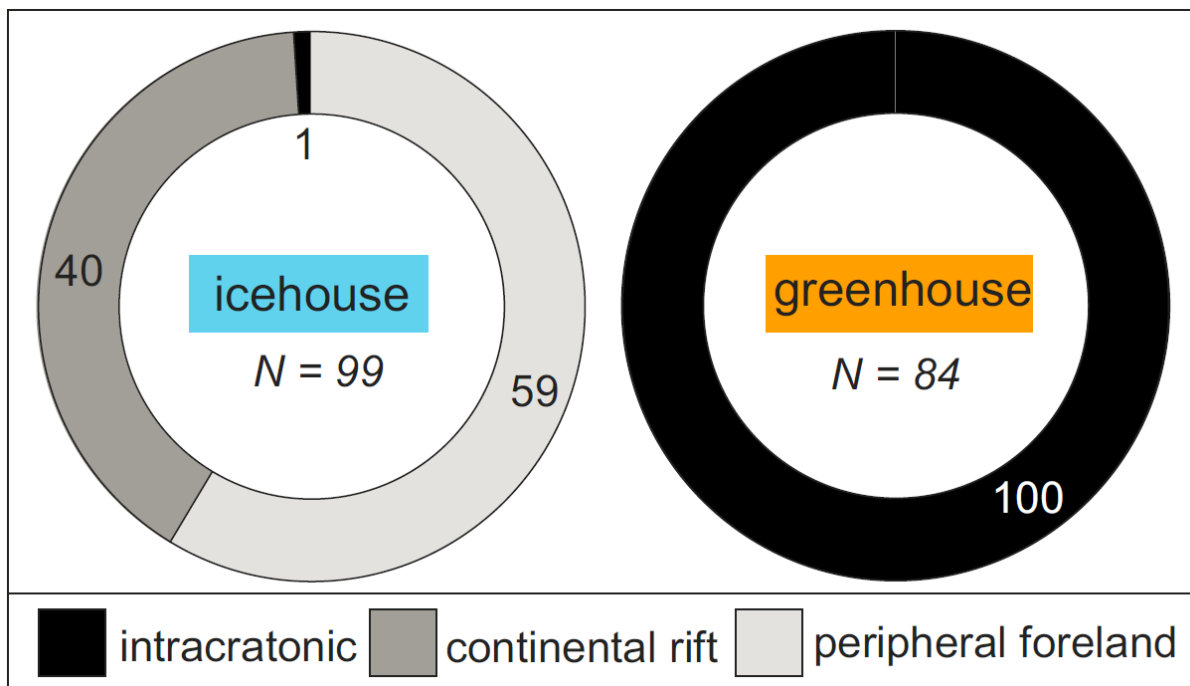
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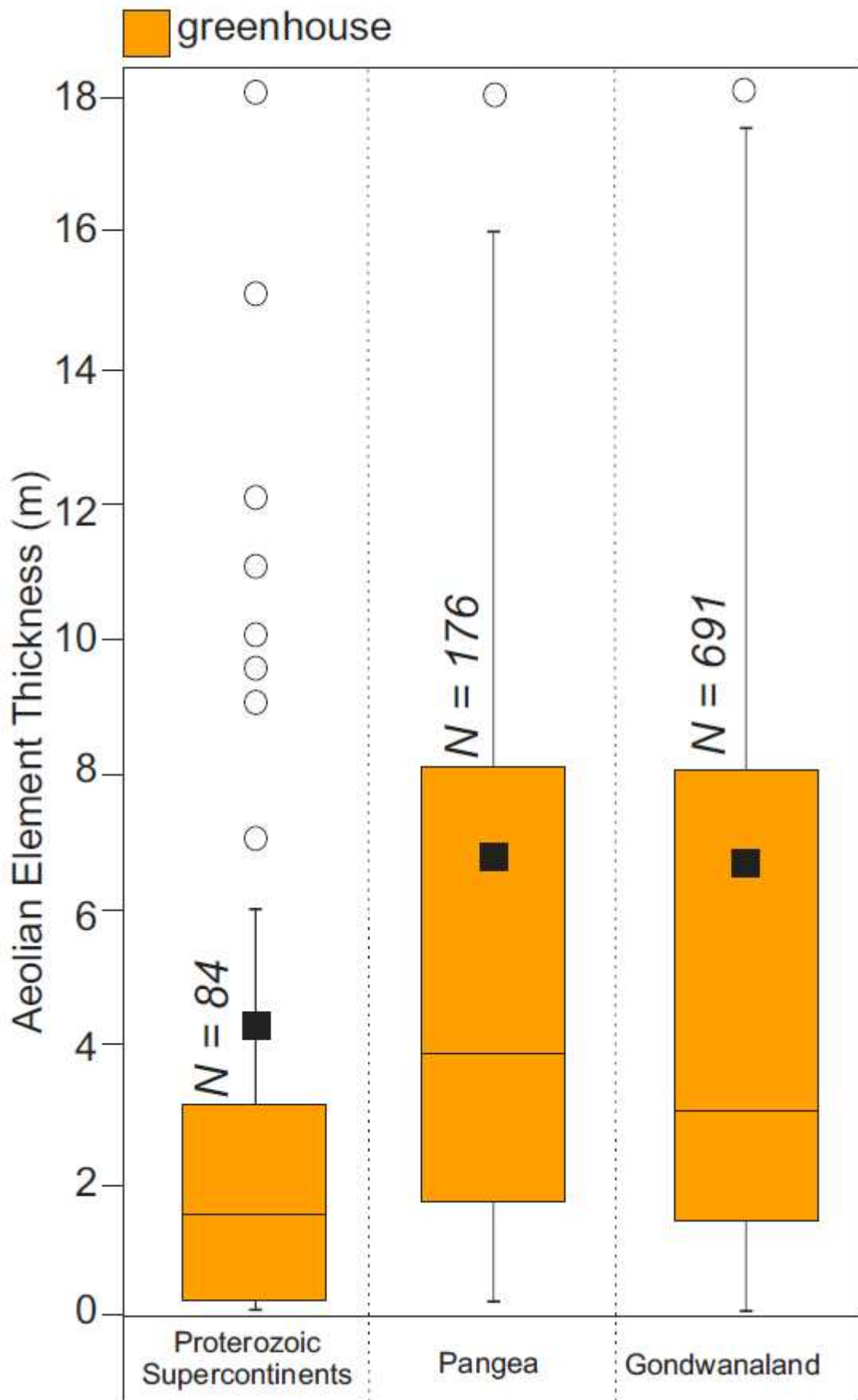


Table 1: Case study details

Case Number	Icehouse or Greenhouse	Age (Ma)	Case Study Name	Location	Reference(s)
1	Greenhouse	ca. 1320 - 1000	Eriksfjord Formation	Greenland	Clemmensen (1988)
2	Icehouse	ca. 259 - 254	Hopeman Sandstone	Scotland, UK	Clemmensen (1987)
3	Icehouse	ca. 290 - 240	Arran Red Beds	Isle of Arran, Scotland, UK	Clemmensen and Abrahamsen (1983)
4	Icehouse	ca. 252 - 242	Sherwood Sandstone	UK (Onshore and Offshore England and Northern Ireland)	Cowan (1993); Meadows and Beach (1993)
5	Icehouse	ca. 299 - 252	Rotliegendes Sandstone	Germany, Poland, Denmark, Baltic Sea, Netherlands	Ellis (1993); Newell (2001)
6	Icehouse	< 1	Boxtel Formation	Netherlands, Germany, Denmark, Poland	Schokker and Koster (2004)
7	Icehouse	ca. 38 - 34	Sable de Fontainebleau Formation	France	Cojan and Thiry (1992)
8	Icehouse	ca. 5	Escorihuela Formation	NE Spain	Liesa et al. (2016)
9	Greenhouse	ca. 132	Etjo Formation	Namibia	Mountney and Howell (2000)
10	Icehouse	ca. 23 - 3	Tsondab Sandstone	Namibia	Kocurek et al. (1999)
11	Icehouse	ca. 1400 - 1327	Egalapenta Formation	India	Biswas (2005); Dasgupta et al. (2005)
12	Greenhouse	ca. 430 - 420	Tumblagooda Formation	Australia	Trewin (1993)
13	Icehouse	ca. 3	Tamala Limestone	Australia	Semeniuk and Glassford (1988)
14	Greenhouse	ca. 140 - 125	Sao Sebastio Formation	Brazil	Formola Ferronato et al. (2019)
15	Greenhouse	ca. 148 - 144	Sergi Formation	Brazil	Scherer et al. (2007)
16	Greenhouse	ca. 1800 - 1600	Mangabeira Formation	Brazil	Ballico et al. (2017)
17	Icehouse	ca. 298 - 272	Caldeirao Formation	Brazil	Jones et al. (2015)
18	Greenhouse	ca. 1800 - 1700	Bandeirinha Formation	Brazil	Simplicico and Basilici (2015)
19	Greenhouse	ca. 163 - 145	Guara Formation	Brazil	Scherer and Lavina (2005)
20	Icehouse	ca. 260 - 257	Piramboia Formation	Brazil	Dias and Scherer (2008)
21	Greenhouse	ca. 129 - 125	Huitrin Formation	Argentina	Strömbäck et al. (2005)
22	Greenhouse	ca. 130 - 129	Agrio Formation	Argentina	Viega et al. (2002)
23	Icehouse	ca. 10 - 4	Rio Negro Formation	Argentina	Zavala and Frieje (2001)
24	Icehouse	ca. 720 - 640	Copper Harbor Formation	Michigan, USA	Taylor and Middleton (1990)
25	Greenhouse	ca. 250 - 245	Chugwater Formation	Wyoming, USA	Irmen and Vondra (2000)

26	Icehouse	ca. 23 - 16	Arikaree Formation	Wyoming, Nebraska, USA	Bart (1977)
27	Icehouse	ca. 299 - 280	Ingleside Formation	Colorado, Wyoming, USA	Pike and Sweet (2018)
28	Icehouse	ca. 299- 280	Lower Cutler Beds	Utah, USA	Jordan and Mountney (2010)
29	Icehouse	ca. 286 - 245	Cedar Mesa Sandstone	Utah, Colorado, New Mexico, Arizona, USA	Loope (1985); Mountney and Jagger (2004); Mountney (2006)
30	Greenhouse	ca. 201 - 191	Navajo Sandstone	Nevada, Arizona, Colorado, Utah, USA	Loope and Rowe (2003)
31	Greenhouse	ca. 166 - 163	Entrada Sandstone	Wyoming, Utah, Arizona, New Mexico, Texas, USA	Crabaugh and Kocurek (1993); Benan and Kocurek (2000); Kocurek and Day (2018)
32	Icehouse	ca. 1000 - 750	Big Bear Formation	California, USA	Stewart (2005)
33	Greenhouse	ca. 227 - 210	Wolfville Formation	Nova Scotia, Canada	Leleu and Hartley (2018)
34	Greenhouse	ca. 170 - 166	Page Sandstone	Arizona, Utah, Wyoming, USA	Jones and Blakey (1997); Kocurek et al. (1992)

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Table 2: List of definitions used in the text

<b>Eolian Architectural Element Types</b>	
Cross-strata package	Packages of aeolian stratification (typically composed of wind-ripple, grainflow and grainfall strata; Hunter 1977, 1981); form parts of dune sets; packages of cross-strata are typically separated by reactivation surfaces (Brookfield, 1977; Kocurek, 1996).
Dune set	Dune-sets form the fundamental unit of deposition of an eolian sand dune; dune-sets are formed of packages of cross-strata (Sorby, 1859; Allen, 1963; Rubin and Hunter 1982; Chrintz and Clemmensen, 1993); if dune sets migrate over each other, cross-stratified packages are truncated, delineating sets that are bounded by erosional surfaces (Brookfield, 1977; Kocurek, 1996).
Dune coset	Two or more genetically related dune sets that occur in vertical succession; both the coset and its contained sets are separated by bounding surfaces (Brookfield, 1977; Kocurek, 1996).
Dune compound set	A specialized class of coset wherein the contained sets record the migration of formative bed forms of a common type, for example where dunes migrate over the flanks of a parent megabedform (draa) which is itself migrating to leave an accumulation; both the compound set and its contained sets are separated by bounding surfaces (Brookfield, 1977; Kocurek, 1996).
Sandsheet	Sandsheet deposits are low-relief accumulations of eolian sediment in areas where dunes are generally absent (Nielsen and Kocurek, 1986; Brookfield, 1992; Rodríguez-López et al., 2012); sandsheets can also comprise low-relief bedforms such as zibars.
Interdune	Interdune deposits are formed in the low-relief, flat, or gently sloping areas between dunes; neighboring dunes are separated by interdunes (Hummel and Kocurek, 1984).
Dry interdune	Dry interdunes are characterized by deposits that accumulate on a substrate where the water table is well below the ground surface, such that sedimentation is not controlled by and is largely not influenced by the effects of moisture (Fryberger et al., 1990).
Damp interdune	Damp interdunes are characterized by deposits that accumulate on a substrate where the water table is close to the ground surface, such that sedimentation is influenced by the presence of moisture (Fryberger et al., 1988; Lancaster and Teller, 1988; Kocurek et al., 1992).

Wet interdune	Wet interdunes are characterized by deposits that accumulate on a substrate where the water table is elevated above the ground surface such that the interdune is episodically or continuously flooded with water (Kocurek and Havholm, 1993; Loope et al., 1995; García-Hidalgo et al., 2002).
<b>Eolian Facies Element Types</b>	
Wind-ripple strata	Wind-ripple lamination forms when wind-blown, saltating grains strike sand-grains obliquely and propel other grains forward (Bagnold, 1941; Hunter, 1977). The foreset laminae of wind-ripple strata are occasionally preserved (rippleform laminae), however, the internal laminae of wind-ripple strata are often indistinguishable due to grain size uniformity (translatent wind-ripple stratification; Hunter, 1977).
Grainflow strata	Grainflow strata form where a dune slipface undergoes gravitational collapse (Hunter, 1977; Bristow and Mountney, 2013). Grainflow deposits are typically erosionally based and are devoid of internal structure, forming discrete tongues or wide sheets of inclined strata on the lee-slope of dunes, which wedge-out towards the base of the dune. Individual grainflow strata may be indistinguishable, resulting in amalgamated grainflow units (Howell and Mountney, 2001).
Grainfall strata	Grainfall strata are gravity-driven deposits that occur when the wind transports saltating clouds of grains beyond a dune brink; grains settle onto the upper portions of lee slopes as wind transport capacities reduce in the lee-side depressions (Nickling et al., 2002). Grainfall laminae are typically thin (<1 mm), drape existing topography, else may have a wedge-shaped geometry; grainfall lamination is generally composed of sand and silt or (rarely) clay sized grains (Hunter, 1977).
Interfingered strata	Interfingered strata represent intercalated packages of wind-ripple, grainflow, grainfall and plane-bed strata; two or more of the aforementioned stratal types may be present. This composite facies type is used only in cases where it is not possible to differentiate individual wind-ripple, grainflow, grainfall or plane-bed facies elements. Interfingered strata can occur in a variety of eolian settings and are especially common on dune lee slopes (Hunter, 1977; Hunter, 1981).
Adhesion strata	Adhesion strata results from the adhesion of moving grains to a damp surface, such as a damp interdune (Hummel and Kocurek, 1984). Adhesion strata typically are low relief (several mm in height) and exhibit sub-horizontal structures with irregular surfaces. Adhesion strata can comprise adhesion plane beds, adhesion ripples (Kocurek and Fielder, 1982) and adhesion warts (Olsen et al., 1989).
Plane-bed strata	Plane-bed lamination forms when wind velocities are too high to form ripples (Hunter 1977, 1981). Plane-bed lamination is composed of (sub)horizontally laminated sand, which typically dips at angles of between 0 and 15° (Pye, 2009). Plane-bed laminae are typically millimeter-scale, with sharp or gradational contacts (e.g., Clemmensen and Abrahamsen, 1983) and form sets typically up to 100 mm (Pye, 2009).
Subaqueous ripple strata	Subaqueous ripple lamination is generated by tractional processes and are produced by the action of waves or currents on a sediment surface (Allen, 1978).
<b>Non-Eolian Element Types</b>	
Fluvial/Alluvial	Deposits arising from or relating to the action of rivers/streams and sediment gravity-flow processes (cf. Melton, 1965).
Marine	Deposits arising from or relating to accumulation in marine environments.
Lacustrine	Deposits arising from or relating to accumulation in perennial lakes.
Sabkha/Playa	Sabkhas and playa lakes describe low-relief flats where evaporites, and in some cases carbonates, accumulate. The terms sabkha and playa lake were originally used to describe coastal and inland settings, respectively (Evans, et al., 1964; Purser and Evans, 1973); however, the terms are now commonly used interchangeably.
Other	Any depositional element that differs in origin from those above.
<b>Surface Types</b>	
Supersurface	Surfaces resulting from the cessation of eolian accumulation; occurs where the sediment budget switches from positive to negative (cannibalization of eolian system) or neutral (zero angle of climb), resulting in deflation ( <i>deflationary supersurface</i> ) or bypass ( <i>bypass supersurface</i> ) of the eolian system, respectively. Supersurfaces are also generated by changes in depositional environment, such as transition from eolian to fluvial, or eolian to marine deposition (e.g., Glennie and Buller, 1983; Chan and Kocurek, 1988).
Wet-type supersurface	Supersurface associated with deflation down to the water-table (also known as a Stokes surface). Wet-type supersurfaces may be associated with aqueous inundation by a non-eolian source (e.g., fluvial/marine deposits).

Damp-type supersurface	Supersurface associated with bypass/deflation; the level of the water table is interacting with the surface.
Dry-type supersurface	Supersurface associated with bypass/deflation; the level of the water table is significantly below the surface.
<b>Basin Types</b>	
Intracratonic (sag) basins	An intracratonic (sag) basin is a depressed or persistently low area occurring in the interior of cratonic blocks or on stable continental crust (Middleton, 1989); they are characterized by generally low rates of accommodation generation, and host sedimentary infills that can be >10 km in thickness and that typically embody over 200-800 Myr (Einsele, 2013).
Rift basin	A continental rift is an elongate graben or half-graben trough (ca. 10 <sup>3</sup> -10 <sup>4</sup> km <sup>2</sup> ) bounded by normal faults, associated with active lithospheric extension and thinning (Gregory, 1894); rift basins are characterized by high rates of accommodation generation (e.g., Rosendahl, 1987; Schlische, 1993; Morley, 1995; Withjack et al., 2002).
Foreland basins	A foreland basin is here defined as a depression generated by flexure of the continental crust in front of a fold-and-thrust mountain belt (Einsele, 2013) and are characterized by intermediate rates of accommodation generation.

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Table 3: Results of statistical analyses						
ARCHITECTURAL AND FACIES ELEMENT THICKNESS						
	<i>EOLIAN ARCH. EL.</i>		<i>NON-EOLIAN ARCH. EL.</i>		<i>FACIES ELEMENTS</i>	
	ICEHOUSE	GREENHOUSE	ICEHOUSE	GREENHOUSE	ICEHOUSE	GREENHOUSE
MEAN	2.36	5.47	5.18	4.88	2.20	7.53
MEDIAN	1.00	2.50	2.00	2.00	1.00	3.75
SD	4.48	8.40	10.07	12.24	3.93	10.23
N	789	903	367	519	630	355
P(T<=t)	0.00		0.35		0.00	
SIGNIFICANT?	TRUE		FALSE		TRUE	
SPECIFIC EOLIAN ELEMENTS						
	<i>DUNE SET</i>		<i>SANDSHEET</i>		<i>INTERDUNE</i>	
	ICEHOUSE	GREENHOUSE	ICEHOUSE	GREENHOUSE	ICEHOUSE	GREENHOUSE
MEAN	3.67	5.93	0.55	4.15	0.88	2.00
MEDIAN	2.00	3.00	0.20	2.00	0.25	1.50
SD	5.54	7.94	0.88	10.33	1.74	2.75
N	440	705	183	171	166	27
P(T<=t)	0.00		0.00		0.00	
SIGNIFICANT?	TRUE		TRUE		TRUE	
EOLIAN TEXTURE						
	<i>GRAIN SIZE</i>		<i>SORTING</i>		<i>ROUNDNESS</i>	
	ICEHOUSE	GREENHOUSE	ICEHOUSE	GREENHOUSE	ICEHOUSE	GREENHOUSE
MEAN	0.34	0.36	0.57	0.58	0.57	0.77

MEDIAN	0.38	0.25	0.50	0.50	0.49	0.85
SD	0.27	0.25	0.19	0.19	0.22	0.12
N	496	310	140	179	113	70
P(T<=t)	0.14		0.43		0.00	
SIGNIFICANT?	FALSE		FALSE		TRUE	
<b>EOLIAN ARCHITECTURAL ELEMENTS BY SUPERCONTINENTAL SETTING</b>						
	<i>PROTEROZOIC SUPERCONTINENTS</i>			<i>PANGEA</i>		
	ICEHOUSE	GREENHOUSE	ICEHOUSE	GREENHOUSE	ICEHOUSE	GREENHOUSE
MEAN	1.43	5.04	3.41	6.85		
MEDIAN	0.80	1.50	2.00	3.86		
SD	2.41	14.44	5.31	7.87		
N	98	84	347	176		
P(T<=t)	0.02			0.00		
SIGNIFICANT?	TRUE			TRUE		
<b>EOLIAN ARCHITECTURAL ELEMENTS BY BASIN SETTING</b>						
	<i>INTRACRATONIC BASIN</i>		<i>CONTINENTAL RIFT BASIN</i>		<i>FORELAND BASIN</i>	
	ICEHOUSE	GREENHOUSE	ICEHOUSE	GREENHOUSE	ICEHOUSE	GREENHOUSE
MEAN	1.73	7.63	0.70	2.48	2.11	4.23
MEDIAN	1.00	3.50	0.15	1.00	2.00	2.50
SD	2.24	10.77	2.00	3.69	1.44	4.47
N	507	595	138	180	191	126
P(T<=t)	0.00		0.00		0.00	
SIGNIFICANT?	TRUE		TRUE		TRUE	
<b>EOLIAN ARCHITECTURAL ELEMENTS BY PALAEO LATITUDE</b>						
	<i>0-15 DEGREES</i>			<i>16-30 DEGREES</i>		
	ICEHOUSE	GREENHOUSE	ICEHOUSE	GREENHOUSE	ICEHOUSE	GREENHOUSE
MEAN	2.60	6.38	2.72	6.40		
MEDIAN	1.00	3.75	1.10	3.00		
SD	4.84	7.08	4.57	9.82		
N	416	261	276	845		
P(T<=t)	0.00			0.00		
SIGNIFICANT?	TRUE			TRUE		
	<i>31-45 DEGREES</i>			<i>46-60 DEGREES</i>		
	ICEHOUSE	GREENHOUSE	ICEHOUSE	GREENHOUSE	ICEHOUSE	GREENHOUSE

MEAN	1.53	1.75	3.39	3.50
MEDIAN	0.30	1.50	2.00	2.00
SD	2.42	1.21	3.92	4.76
N	168	35	57	142
P(T<=t)	0.30		0.44	
SIGNIFICANT?	FALSE		FALSE	

**EOLIAN ARCHITECTURAL ELEMENTS BY ERG DISTALITY**

	<i>BACK ERG</i>		<i>CENTER ERG</i>		<i>FORE ERG</i>	
	ICEHOUSE	GREENHOUSE	ICEHOUSE	GREENHOUSE	ICEHOUSE	GREENHOUSE
MEAN	1.65	2.92	3.39	12.83	1.87	6.36
MEDIAN	0.75	2.00	1.50	10.00	1.20	3.00
SD	2.79	3.22	5.96	11.75	1.81	7.37
N	152	467	252	268	41	205
P(T<=t)	0.00		0.00		0.00	
SIGNIFICANT?	TRUE		TRUE		TRUE	

**COMPARISONS OF GREENHOUSE PANGEA DEPOSITS WITH OTHER GREENHOUSE SUPERCONTINENTAL SETTINGS**

	GREENHOUSE ONLY		GREENHOUSE ONLY	
	<i>PANGEA</i>	<i>GONDWANALAND</i>	<i>PANGEA</i>	<i>PROTEROZOIC SUP.</i>
MEAN	6.85	6.70	6.85	4.26
MEDIAN	3.88	3.00	3.88	1.50
SD	7.87	9.43	7.87	12.63
OBSERVATIONS	176	691	176	84
ANOVA	0.85		0.04	
SIGNIFICANT?	FALSE		FALSE	

**SUPERSURFACE SPACING**

	ICEHOUSE	GREENHOUSE
MEAN	16.34	9.07
MEDIAN	16.00	9.00
SD	12.70	6.34
OBSERVATIONS	25	7

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