Eolian Stratigraphic Record of Environmental Change Through Geological Time

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ABSTRACT

The terrestrial sedimentary record provides a valuable archive of how ancient depositional systems respond to and record changes in the Earth's atmosphere, biosphere and geosphere. However, the record of these environmental changes in eolian sedimentary successions is poorly constrained and largely unquantified. This study presents the first global-scale, quantitative investigation of the architecture of eolian systems through geological time via analysis of 55 case studies of eolian successions. Eolian deposits accumulating 1) under greenhouse conditions, 2) in the presence of vascular plants and grasses, and 3) in rapidly subsiding basins, associated with the rifting of supercontinents, are represented by significantly thicker eolian dune-set, sandsheet and interdune architectural elements. Pre-vegetation eolian systems are also associated with more frequent interactions with non-eolian environments. The interplay of these forcings has resulted in dune-set thicknesses that tend to be smallest and largest in Proterozoic and Mesozoic successions, respectively. In the Proterozoic, the absence of sediment-binding plant roots rendered eolian deposits susceptible to post-depositional wind deflation and reworking by fluvial systems, whereby highly mobile channels reworked contiguous eolian deposits. During the Mesozoic, humid greenhouse conditions (associated with relatively elevated water-tables) and high rates of basin subsidence (associated with the break-up of Pangea) favored the rapid transfer of eolian sediment beneath the erosional baseline. The common presence of vegetation promoted accumulation of stabilizing eolian systems. These factors acted to limit post-depositional reworking. Eolian sedimentary deposits record a fingerprint of major

environmental changes in Earth history: climate, continental configuration, tectonics, and land-plant evolution.

INTRODUCTION

Eolian sedimentary systems are sensitive to environmental forcings, notably climate (Clemmensen et al., 1994; Cosgrove et al., 2021a), tectonic configuration (Blakey et al., 1988), basin subsidence (Kocurek and Havholm, 1993; Howell and Mountney, 1997; Cosgrove et al., 2021c), and the presence and type of vegetation (Gibling and Davies, 2012; Santos et al., 2017, 2019). The preserved eolian sedimentary record archives the response of eolian systems to changing environmental forcings through geological time. However, despite a global sedimentary record, comparisons between eolian systems developed under different environmental conditions are not straightforward: many depositional models are qualitative and commonly derived from individual case studies (e.g. Kocurek and Dott, 1981; Mountney and Jagger, 2004; Rodríguez-López et al., 2014).

Here, we undertake the first comprehensive comparison of the preserved architectures of eolian systems accumulated and preserved through geological time. We consider 1) the thickness of eolian architectural elements, 2) the relative proportion of different types of eolian elements, and 3) the relationships of eolian strata with contiguous non-eolian deposits. The aim is to quantify variations in eolian architectures at multiple scales of observation through geological time, and to interpret these changes in terms of potential controls. Specific research objectives are 1) to determine which environmental forcings markedly influence eolian architecture, and 2) to determine how these forcings have acted and interacted though geological time.

DATA AND METHODS

This study utilizes the Database of Aeolian Sedimentary Architecture (DASA; Cosgrove et al., 2021a, b, & c), which stores data on eolian and interdigitated non-eolian geological entities. Data considered here are collated from 58 published accounts associated with 55 eolian successions. A location map of all case studies and an account of the source literature is provided in Supplementary Information 1 and 2, respectively. Each case study is associated with data on its geological background, derived from the wider literature, and including geological age, tectonic setting, prevailing climate conditions, and basin subsidence rates (gathered from total-subsidence curves available in the wider literature; see Cosgrove et al. 2021c).

Primary data have been extracted from published accounts, such as sedimentary logs or outcrop panels. Herein, architectural elements are considered in detail, and defined as distinct sedimentary bodies that are the product of deposition in a specific sub-environment. Definitions of architectural-element types mentioned in the text are given in Supplementary Information 3. Architectural elements are classified on interpreted origin (e.g., dune, interdune, sandsheet); their maximum observed thickness is recorded. The proportions of architectural elements in successions, or parts thereof, is considered as fractions of total recorded thicknesses.

To enable comparisons between eolian systems developed under different environmental conditions, case studies and data extracted therefrom are grouped according to 1) prevailing climatic conditions (icehouse versus greenhouse), 2) supercontinental setting, 3) the presence or absence of land plants and grasses, and 4) rates of basin subsidence. In addition, data are grouped according to geological age (Proterozoic, Paleozoic, Mesozoic and Cenozoic), to determine the importance of environmental forcings through time.

Statistical analysis has been undertaken on element thickness data. Two-tailed t-tests and Independent Group ANOVA have been used to compare mean thicknesses across eolian systems. An α value of 0.05 is considered for all statistical analyses.

RESULTS

In the text, for brevity, mean thicknesses are reported; for values of median, standard deviation and number of observations, refer to Table 1. All data shown in the figures are reported in Supplementary Information 4.

Environmental Forcings

Through geological time, the Earth’s climate has fluctuated between two end-member climatic conditions: icehouse and greenhouse, respectively defined by the presence or absence of major continental ice-sheets and polar ice (Frakes et al., 1992). Data are grouped according to the prevailing climatic conditions at the time of eolian accumulation (Fig.1A). When all eolian elements are considered, their mean thicknesses are 2.7 m and 4.1 m for icehouse and greenhouse successions, respectively. Greenhouse eolian elements are significantly thicker than their icehouse counterparts ($P<0.01$; Table 1).

Continental masses have undergone cycles of supercontinent assembly and subsequent break-up through geological time (Condie, 2016). Data are grouped according to supercontinental settings (Fig. 1B). Mean thicknesses of eolian elements are 1.9 m, 1.5 m, 2.8 m, 7.4 m, and 2.8 m for 1) Proterozoic Rodinia and Pannotia, 2) Gondwana, 3) Pangea, 4) Laurasia and Gondwanaland, and 5) dispersed continental settings, respectively. There is a significant difference amongst groups ($P<0.01$; Table 1). The thickest eolian elements are associated with the supercontinents Laurasia and Gondwana (175 – 65 Ma, following the break-up of Pangea).

Rates of basin subsidence are grouped into slow (1-10 m/Myr), moderate (10-100 m/Myr), and rapid (>100 m/Myr) rates (Fig. 1D). When all eolian elements are considered, mean thicknesses are 2.0 m, 3.4 m, and 8.7 m in slowly, moderately, and rapidly subsiding basins, respectively. Mean differences across groups are statistically significant ($P<0.01$; Table 1).

Vascular land plants and grasses evolved at ca. 420 and ca. 66 Ma, respectively (Boyce and Lee, 2017). Data are therefore grouped into bins of 2400 – 420 Ma (eolian accumulation prior to the widespread evolution of vascular land plants), 420 – 66 Ma (accumulation in the presence of vascular land plants), and 420 – 0 Ma (accumulation in the presence of vascular land plants and grasses; Fig. 1C). When all eolian elements are considered, mean thicknesses are 2.3 m, 4.5 m, and 4.3 m, for eolian systems deposited in ranges of 2400 – 420 Ma, 420 – 66 Ma, 420 – 0 Ma, respectively. A significant difference amongst groups is present ($P<0.01$; Table 1). Eolian elements developed in the absence of vascular land plants are significantly thinner than those developed under the presence of vascular land plants.

Geological Age

Eolian systems are grouped as deposits of Proterozoic (2400-541 Ma), Paleozoic (451-252 Ma), Mesozoic (252-66 Ma), and Cenozoic (<66 Ma) age (Fig. 2A). When all eolian elements are considered, mean thicknesses are 2.2 m, 2.2 m, 6.7 m, and 2.8 m in these age groups, respectively. There is a significant difference in the mean thicknesses of dune-sets, sandsheets and interdunes ($P < 0.01$), across age groups (Table 1).

Ratios of eolian to non-eolian elements as a fraction of the stratigraphy are 61:39, 73:27, 72:28, and 79:21 in the Proterozoic, Paleozoic, Mesozoic and Cenozoic, respectively. Dune-sets form 46%, 86%, 81% and 89%, sandsheets form 49%, 7%, 4%, and 4%, interdunes form 5%, 7%, 15%, and 7% of the total recorded aeolian stratigraphy, in the Proterozoic, Paleozoic, Mesozoic and Cenozoic, respectively. Dune-sets have mean thicknesses of 1.9 m, 3.0 m, 7.8 m, and 5.8 m, sandsheets have mean thicknesses of 3.6 m, 1.0 m, 3.6 m, and 0.4 m, interdunes have mean thicknesses of 0.8m, 0.7 m, 2.5 m, and 0.8 m in the Proterozoic, Paleozoic, Mesozoic, and Cenozoic, respectively. The non-eolian lithology is dominantly marine (52%) and fluvial (39%) in the Proterozoic; fluvial (62%) and alluvial (15%) in the Paleozoic; fluvial (67%) and sabkha (14%) in the Mesozoic; and fluvial (42%) and marine (32%) in the Cenozoic.

Environmental Controls through Geological Time

Environmental controls, for example, the assembly and break-up of supercontinents, or prevailing icehouse and greenhouse conditions, can span only parts of a geological era, or multiple geological eras. As such, for each era, the percentage of recorded architectural elements deposited under given environmental conditions are presented (Fig. 3A).

DISCUSSION

Climate

Greenhouse eolian elements are significantly thinner than their icehouse counterparts (Table 1; Fig. 1A). Under icehouse conditions, eolian systems are subject to episodes of glacial accumulation and interglacial deflation, which are driven by Milankovitch-type cyclicity (Milankovitch, 1941). During glacials, drier conditions are associated with strengthened Trade Winds and depressed water-tables: eolian deposits are therefore more likely to be exposed above the baseline of erosion for extended periods, and are thus prone to deflation and reworking (Kocurek and Havholm, 1993; Cosgrove et al., 2021a). Conversely, under greenhouse conditions high eustatic sea levels and relatively more humid conditions generally promote elevated water tables situated close to the accumulation surface, allowing eolian elements to be rapidly sequestered beneath the erosional baseline and protected from post-depositional reworking (Kocurek et al., 2001). Uniquely in the Mesozoic, eolian accumulation occurred exclusively under greenhouse conditions, which may partly account for the preservation of significantly thicker eolian elements. The roles of humid greenhouse conditions can be inferred by the high percentage of sabkha elements, which is greater than in other eras (Fig. 2B).

In the Cenozoic, despite the majority of eolian elements being deposited under icehouse conditions – associated with thinner eolian elements – average dune-set thickness is the second thickest in geological history (Figs. 2A, 3A). Many relatively thick Cenozoic dune-sets are an artefact of preservational biases in that they are not yet truly preserved in a long-term sense as they lie above the level of a long-term erosional baseline: they are accumulated but not yet preserved (*sensu* Kocurek and Havholm, 1993). However, comparisons between Quaternary (<2.6 Ma) and earlier Cenozoic deposits suggest a more complicated relationship: Quaternary deposits are significantly ($P=<0.01$) thinner than their Paleogene (ca. 66-23 Ma) and Neogene (ca. 23-2.6 Ma) counterparts (Table 1). The relative thickness of Cenozoic dune-sets might be due to the evolution of stabilizing grasses at ~66 Ma, which limit the capacity for eolian deflation (see below).

Vegetation

Eolian elements deposited in the presence of vascular land plants and grasses are significantly thicker than those that were deposited in their absence (Fig. 1C; Table 1). In the absence of vegetation, substrates lack sediment-binding plant roots; this tends to result in the increased mobility of fluvial channels, which can more easily wander across eolian landscapes and rework eolian sediments (Davies et al., 2011; Santos et al., 2017, 2019; Basilici et al., 2021a). The absence of vascular land plants in the Proterozoic and early Paleozoic (Boyce and Lee, 2017; Fig. 3A) may, in part, account for the preservation of relatively thin eolian dune-sets, and relatively high percentages of sandsheets during these time periods. Sandsheets can represent the erosional remnants of landforms of originally higher relief; their occurrence can represent the reworking of dune bedforms by fluvial processes (Nielsen and Kocurek, 1986). The highest recorded percentage of interdigitating non-eolian elements in Proterozoic successions can be interpreted in these terms (Fig. 2B).

The radiation of grasses at 66 Ma has likely further limited the mobility of Cenozoic river systems (Davies-Colley, 1997; Fig. 3). Moreover, grasses play a crucial role in dune construction and stabilization, by disrupting primary airflows in the near-surface layer, decelerating winds and causing the fall-out of airborne sand (Nielsen and Kocurek, 1986; Jackson et al., 2019). After sediment deposition, grasses can effectively trap eolian sediment, inhibiting re-suspension and erosion (Byrne and McCann, 1990; Ruz and Allard, 1994). Grasses can inhibit the deflation of dune-sets, and a record of this can be interpreted in the low percentage of sandsheets in Cenozoic eolian stratigraphies; the stabilizing effects of grasses act to markedly retard eolian winnowing, thereby reducing the supply of sediment suitable for sandsheet accumulation (Nielsen and Kocurek, 1986).

Basin Subsidence and Supercontinental Setting

Long-term eolian preservation requires the generation of accommodation in which deposits can accumulate - most obviously provided by the subsidence of active sedimentary basins (Kocurek and Havholm, 1993). Mesozoic systems developed in basins with significantly higher rates of subsidence (Fig. 2A); they record the highest proportion of stratigraphy accumulated in rapidly subsiding basins (Fig. 3A). Rapid Mesozoic subsidence may correspond with the break-up of Pangea, during which continental rifting led to the formation of Laurasia and Gondwana (Blakey et al., 1988; Condie, 2016). Rapid subsidence enables a faster rate of rise of the level of the accumulation surface, which allows bedforms to climb at steeper angles (Kocurek and Havholm, 1993; George and Berry, 1997; Howell and Mountney, 1997; Paim and Scherer, 2007; Cosgrove et al., 2021c), leading to the preservation of thicker eolian elements.

Conversely, the Proterozoic has the highest percentage of eolian elements accumulated in slowly subsiding basins, where eolian elements are thinnest on average (Figs. 2A, 3A). The slow generation of accommodation may have favored the accumulation and preservation of relatively thin genetic eolian units, whereby eolian dune-sets likely climbed at low-angles and accumulated sporadically between long episodes of sediment bypass under conditions of low rates of accommodation generation (e.g. Basilici et al., 2020b; Cosgrove et al., 2021c). Proterozoic systems may be affected by preservational biases, such that the outcropping remains of Proterozoic supercontinents are preferentially preserved in intracratonic basins in ancient, stable continental interiors (Shaw et al., 1991; Aspler and Chiarenzelli, 1997); basins of this type tend to experience slower subsidence rates compared to other settings (Xie and Heller, 2009). However, preserved deposits of Proterozoic eolian systems accumulated in more rapidly subsiding basins are also known (e.g. eolian systems from the rift-sag Espinhaço Basin; Simplicio and Basilici, 2015; Abrantes et al., 2020; Mesquita et al., 2021).

CONCLUSIONS

This study presents the first large-scale quantitative assessment of how environmental forcings have influenced eolian architecture through geological time. Significant differences in eolian architecture are attributed to the interplay of 1) climate, 2) continental configuration, 3) land-plant evolution, and 4) basin subsidence (Fig. 3). The independent effect of each of these forcings on the eolian stratigraphic record has been demonstrated statistically. Each of these forcings may span only parts of a geological era, or multiple geological eras, leading to complex interactions between forcing mechanisms throughout Earth history. Results presented here demonstrate how eolian successions record variations in eolian landscapes and sediment preservation mechanisms in response to changes in the Earth's atmosphere, biosphere and geosphere.

ACKNOWLEDGMENTS

We thank the sponsors and partners of FRG-SMRG-ERG for financial support for this research. Claiton Scherer and two anonymous reviewers are thanked for their useful comments.

FIGURE CAPTIONS

1) Thicknesses of eolian and non-eolian architectural elements subdivided by: A) climate (data are grouped into icehouse and greenhouse periods), B) supercontinental setting, C) the presence and type of vegetation, and D) rates of basin subsidence. The legend describing all box and whisker plots is shown in Part C. Outliers are not presented.

2) Variations through geological time in: A) thicknesses of eolian and non-eolian architectural elements and rates of basin subsidence (outliers are not presented); B) assemblages of architectural elements.

3) A) Percentages of recorded architectural elements deposited under a variety of environmental conditions; B) environmental forcings governing eolian construction, accumulation and preservation through geological time.

TABLE CAPTIONS

1) Results of statistical analyses. Unless otherwise stated, analysis has been completed on all eolian architectural element types.

SUPPLEMENTARY FILES

Supplementary Figure 1) Location map of the 55 ancient eolian case-studies.

Supplementary Table 1) List of case-studies and associated source literature.

Supplementary Table 2) Definitions of architectural elements and types discussed in the text.

Supplementary Table 3) Data used to generate the results presented here.

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Figure 1

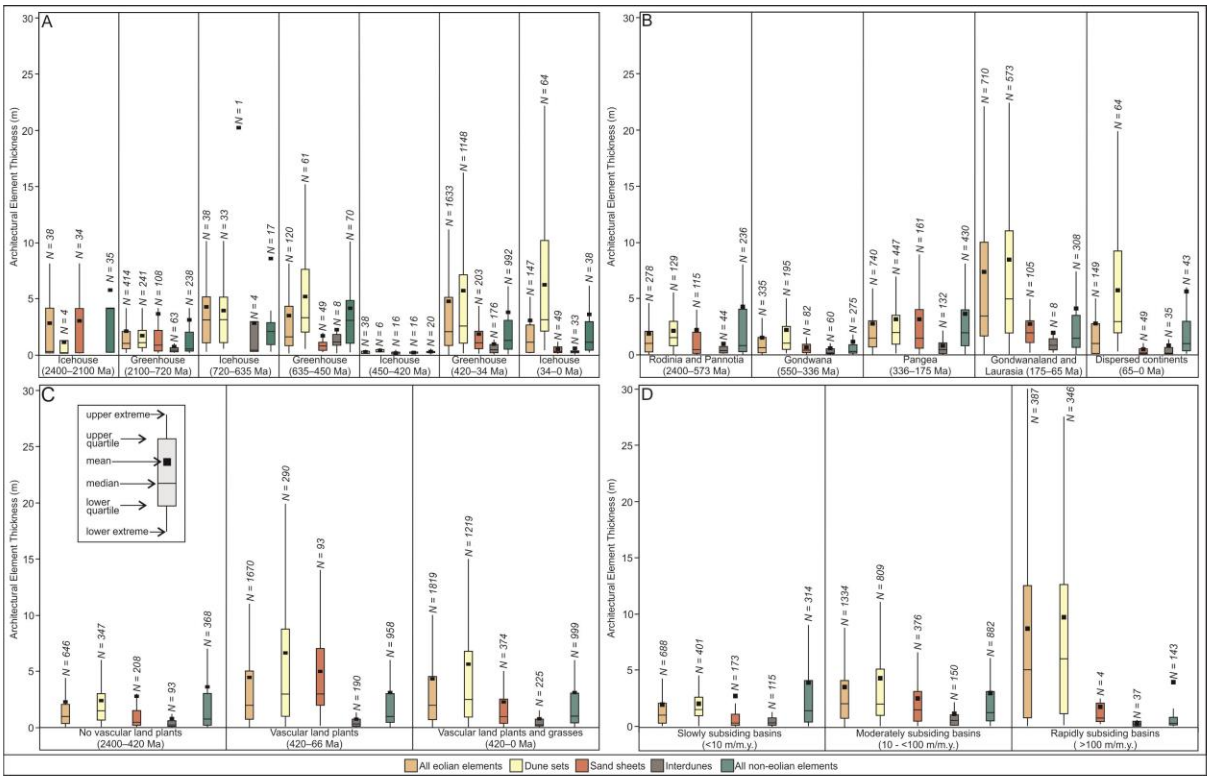


Figure 2

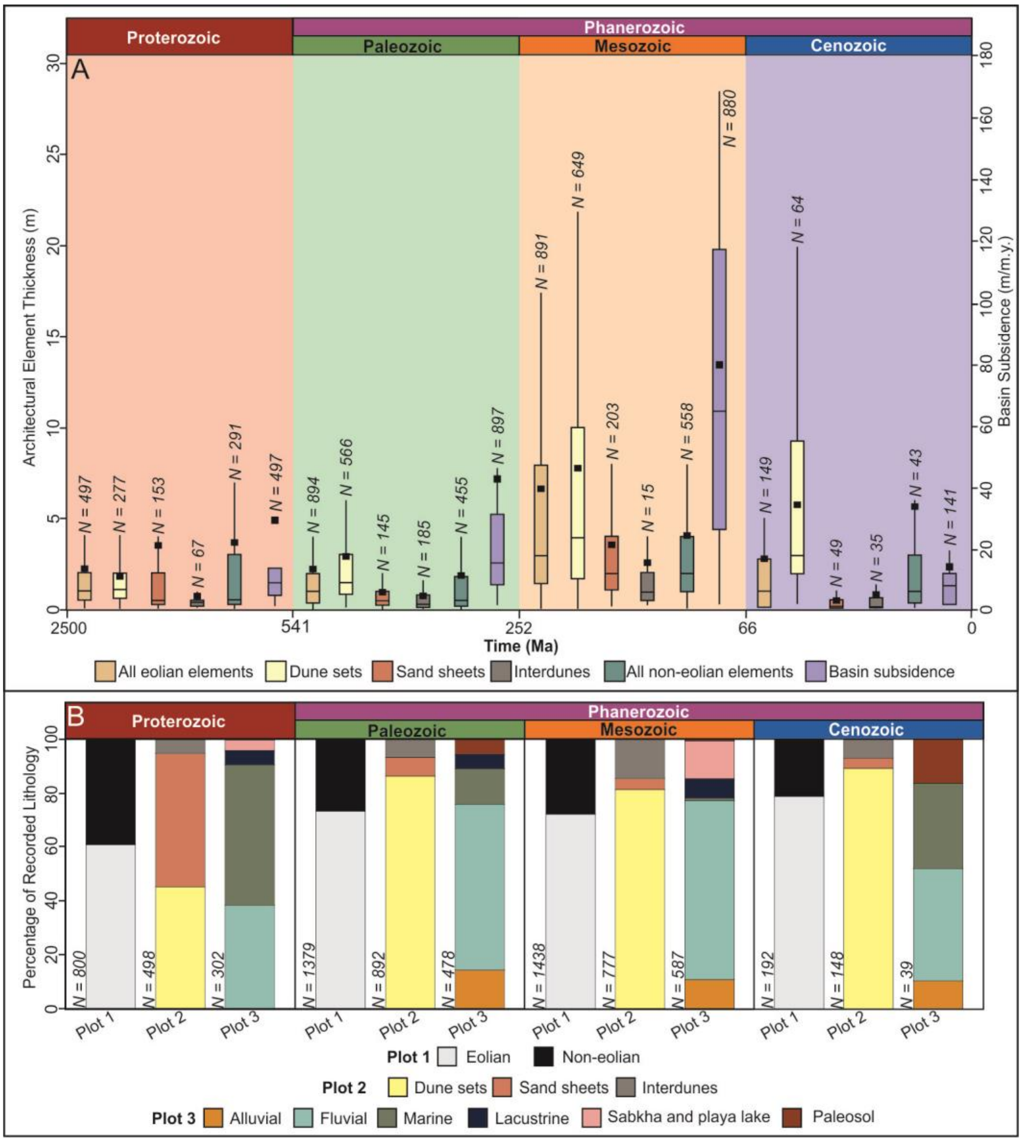
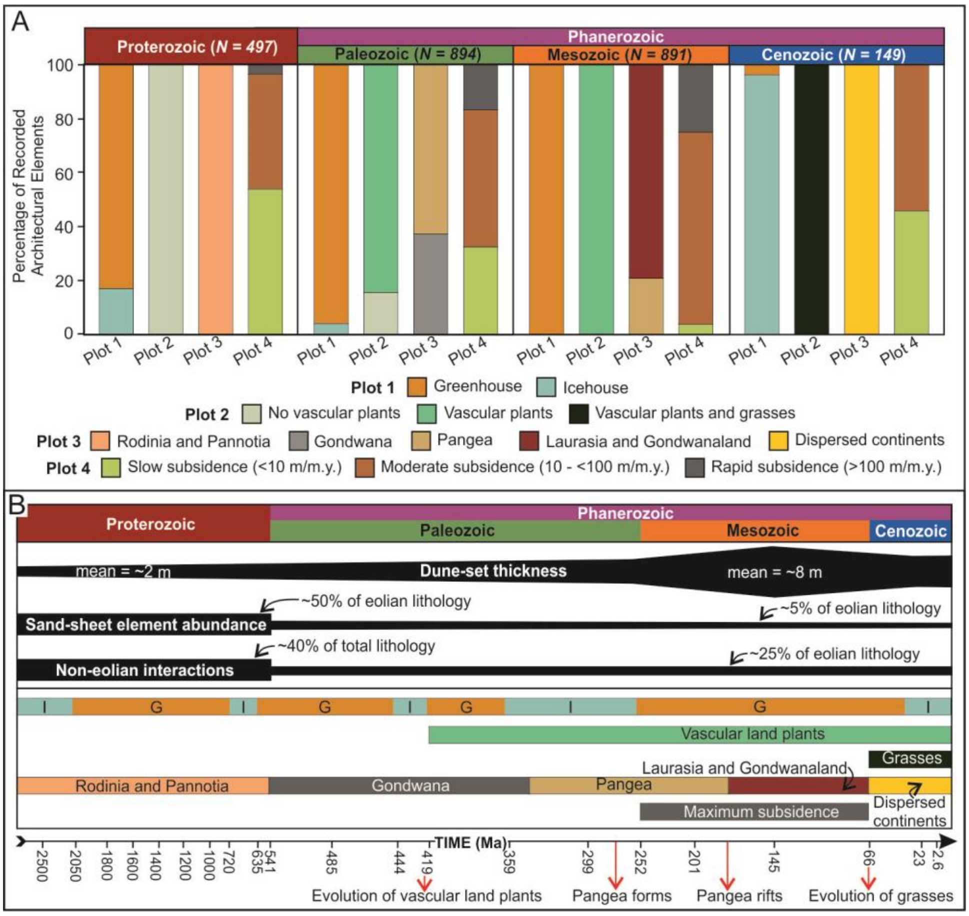


Figure 3


A
Proterozoic (N = 497)
Phanerozoic
Paleozoic (N = 894)
Mesozoic (N = 891)
Cenozoic (N = 149)
Percentage of Recorded Architectural Elements
Plot 1 Plot 2 Plot 3 Plot 4
Plot 1 Greenhouse Icehouse
Plot 2 No vascular plants Vascular plants Vascular plants and grasses
Plot 3 Rodinia and Pannotia Gondwana Pangea Laurasia and Gondwanaland Dispersed continents
Plot 4 Slow subsidence (<10 m/m.y.) Moderate subsidence (10 - <100 m/m.y.) Rapid subsidence (>100 m/m.y.)
B
Proterozoic
Phanerozoic
Paleozoic
Mesozoic
Cenozoic
mean = ~2 m
Dune-set thickness
mean = ~8 m
~50% of eolian lithology
Sand-sheet element abundance
~5% of eolian lithology
~40% of total lithology
Non-eolian interactions
~25% of eolian lithology
Vascular land plants
Grasses
Laurasia and Gondwanaland
Rodinia and Pannotia
Gondwana
Pangea
Maximum subsidence
Dispersed continents
TIME (Ma)
Evolution of vascular land plants
Pangea forms
Pangea rifts
Evolution of grasses