Precambrian Research 402 (2024) 107286

Contents lists available at ScienceDirect

Precambrian Research

journal homepage: www.elsevier.com/locate/precamres

The Precambrian continental record: A window into early Earth environments

Grace I.E. Cosgrove [a,*], Luca Colombera [b], Nigel P. Mountney [a]

[a] School of Earth and Environment, Institute of Applied Geoscience, University of Leeds, Woodhouse, Leeds LS2 9JT, UK
[b] Dipartimento di Scienze della Terra e dell'Ambiente, Università di Pavia, Via Ferrata 1, 27100 Pavia, Italy

ARTICLE INFO

Keywords:
Fluvial
Aeolian
Lacustrine
Glacial
Palaeoclimate
Palaeoenvironment

ABSTRACT

The Precambrian was characterized by unique palaeoenvironmental conditions in the Earth's atmosphere, biosphere and geosphere. This study presents a global quantitative analysis of Precambrian sedimentary successions of aeolian, alluvial, fluvial, lacustrine and glacigenic origins, examined in the broader context of Earth evolution. In the Precambrian, an apparent scarcity of aeolian successions is observed. This may be linked to: (1) differences in atmospheric density, which controlled wind erosion and sedimentation; (2) different astronomical configurations, which may have influenced tides and atmospheric circulation, thereby affecting sand availability and the width of subtropical zones; (3) potentially hotter and more humid climates, restricting dry-sand availability; (4) a lack of vascular vegetation that could prevent reworking of aeolian deposits; (5) poor preservation potential; (6) misinterpretation of the Precambrian record. Mixed aeolian-alluvial strata are more abundant, perhaps because their preservation in the geological record was favoured by water tables sustained by incursions of alluvial systems into otherwise aeolian dominated environments. Aeolian deposits were preferentially accumulated during phases of supercontinental breakup, where rapidly subsiding rift basins provided accommodation suitable for preservation. Other than in the Neoproterozoic record, where glacigenic deposits dominate, alluvial strata are the most common and thickest type of continental deposit in the Precambrian. Precambrian braided alluvial systems were more widespread than in the Phanerozoic. Major alluvial systems formed preferentially during phases of supercontinent assembly, whereby alluvial systems drained major orogens, and long drainage pathways developed from supercontinent interiors to coastlines. In the Paleoproterozoic, ephemeral, saline to partly arid lakes developed extensively in the desertic interior of Columbia. Glacial deposits preferentially formed in the breakup phase of supercontinental cycles; this supports theories invoking enhanced chemical weathering of uplifted rift shoulders as a driver of carbon dioxide sequestration, global cooling, and glaciation. Overall, the number of identified continental successions increases towards the Precambrian-Phanerozoic boundary. This may be an artefact of an increasingly more complete stratigraphic record as time progresses. However, the abundance of continental successions varies on a quasi-periodic cycle of 500 – 700 Myr, with peaks coinciding with the tenure and breakup of Precambrian supercontinents.

1. Introduction

The Precambrian accounts for ca. 88 % of geological time (ICS, 2022). Yet, the significant majority of sedimentological studies have focussed on the Phanerozoic sedimentary record, for the following reasons: 1) generally better preservation (Bose et al., 2012; 2) a geological record that is more widely exposed on the Earth's surface today (e.g., Goodwin, 1991); 3) a better fossil record, making it easier to determine a detailed biostratigraphic framework (Eriksson et al., 2005). Nevertheless, the Precambrian sedimentary record provides a unique opportunity to gain an improved understanding of the evolution of the early Earth's atmosphere, hydrosphere, biosphere, and geosphere (Eriksson et al., 2000, 2001; Young, 2004, 2013, 2018; Bose et al., 2012; Basilici et al., 2020, 2021).

The Precambrian terrestrial record is associated with a set of geologically unique palaeoenvironmental conditions, summarized as follows. 1) An absence of vascular, rooted, terrestrial vegetation and the limited development of soils, which directly affected rates of weathering, erosion and sediment supply (Cotter, 1978; Eriksson et al., 1998; Tirsgaard, and Øxnevad, 1998; Donaldson et al., 2002; Lebeau and Lelpi,

* Corresponding author.
E-mail address: g.i.e.cosgrove@leeds.ac.uk (G.I.E. Cosgrove).

https://doi.org/10.1016/j.precamres.2023.107286
Received 10 July 2023; Received in revised form 13 September 2023; Accepted 28 December 2023
Available online 14 January 2024

2017). 2) An absence of widespread biogenic activity and bioturbation until ca. 600 Ma, with the exception of microbial activity, including the formation of microbial mats in many terrestrial environments (Eriksson et al., 2000, 2001; Schieber, 2004; Sarkar et al., 2005; Schieber et al., 2007; Basilici et al., 2020). In the absence of eukaryote grazers and vascular vegetation, microbial mats may have been widespread on land (e.g., Watanabe et al., 2000; Finke et al., 2019; McMahon et al., 2021); tough and relatively erosion-resistant microbial mats and films influenced physical and chemical processes of weathering and erosion (Belnap, 2001). 3) Atmospheric pressures and densities may have varied considerably to those present today, potentially influencing the way that wind-blown sediment moved (Kok et al., 2012; Runyon et al., 2017; Goosman et al., 2018). Different studies with antithetical views indicate either relatively lighter or denser Precambrian atmospheric conditions (e.g., Som et al., 2012, 2016; Marty et al., 2013; Kavanagh and Goldblatt, 2015; Avice et al., 2018; Catling and Zahnle, 2020). 4) Astronomical variability, including the closer proximity of the Moon (e.g., Darwin, 1880; Turcotte et al., 1977; Davies et al., 2023) and the faster rotation rate of the Earth compared to the present (e.g., Touma and Wisdom, 1994), may have influenced various aspects of Earth's environments, including tides, the number, distribution and extent of atmospheric climate circulation cells, and global mean wind velocities. In turn, these factors may have influenced patterns of aeolian transport and deposition during the Precambrian.

Collectively, these conditions may have governed patterns of sedimentation through time, influencing the rates and intensities of processes controlling weathering, erosion, transport, deposition, lithification and diagenesis (Bose et al., 2012). However, the extent to which this unique set of palaeoenvironmental conditions may have influenced patterns of sedimentation in the Precambrian remains to be determined. This article aims to resolve this, by evaluating the palaeoenvironmental significance of known Precambrian sedimentary successions of aeolian, alluvial, lacustrine and glacial origin.

2. Methods

A comprehensive review of 378 literature case studies has been undertaken to document known examples of: 1) aeolian deposits (18 cases; Fig. 1; Table S1); 2) mixed aeolian-alluvial deposits (31 cases; Fig. 1; Table S2); 3) alluvial deposits (171 cases; Fig. 1; Table S3); 4) lacustrine deposits (42 cases; Fig. 1; Table S4); and 5) glacigenic deposits (116 cases; Fig. 1; Table S5).

Alluvial deposits are defined here as comprising all continental deposits created by streamflows, usually in the form of rivers, and the products of alluvial mass transport. Aeolian deposits comprise the products of wind-blown sediment (i.e. dunes, sandsheets and interdunes). Aeolian and alluvial deposits may occur interdigitated with each other (classified here as mixed aeolian-alluvial deposits), else with the products of other depositional environments, such as marine or evaporative deposits. Due to the apparent frequent and extensive interactions between aeolian and alluvial environments in Precambrian terrestrial systems, mixed aeolian-alluvial deposits are classified separately in this work.

Herein, lacustrine deposits are subdivided into 'non-saline' and 'saline to partly arid' classifications (Table S4). The former refers to freshwater lakes, which are typically hydrologically open. The latter refers to lakes in which evaporation exceeds precipitation, resulting in a high concentration of salts and other dissolved minerals; a salinity value of at least 3 g l^{-1} demarcates saline from non-saline lakes (Waiser and Robarts, 2009). Saline to partly arid lakes can be permanent or ephemeral; often these lakes have highly variable water inflows and vary in depth, area and salinity as they experience relatively wet and dry periods (Williams and Mann, 2023). Some lacustrine case studies (e.g., the Arai Formation) are given multiple salinity interpretations – i.e., they are interpreted as both 'non-saline' and 'saline to partly arid' – where there is evidence of changing salinity conditions through time. Lacustrine systems are also classified according to the drainage type; exorheic lacustrine systems are defined as open systems in which surface waters ultimately drain to the ocean and encompass fluvial systems temporarily impounded by perennial lacustrine systems (Williams and Mann, 2023). Endorheic lacustrine systems are defined as hydrologically closed systems, which do not drain to the sea or other water bodies; rather, surface waters drain to inland termini (Williams and Mann, 2023).

Herein, 'glacigenic' refers to any deposit for which a glacial influence may be identified. It is acknowledged that the primary sedimentary products of glaciers may be later considerably reworked and deposited in other settings (e.g. Nystuen, 1985). Glacigenic deposits include glacio-marine deposits (e.g., glaciomarine tillites), which carry a record of terrestrial processes: terrestrial glaciers flow under the influence of gravity and move toward the coastline (in many cases marine), picking up and carrying sediment from the land, potentially of all grain sizes. The implication of glaciated continents is key for the scope of the paper; as such, to ensure a full and complete analysis, glacio-marine deposits (e.g., Young and Gostin, 1991; Strand and Laajoki, 1993) have been included in the study.

A case study is defined as a record of a terrestrial Precambrian sedimentary succession of given origin (e.g., the Mangabeira Formation; Bállico et al., 2017). Here 'terrestrial' is defined as relating to the Earth's land surface; coastal (tidal, supratidal, estuarine and shallow marine) deposits are not included. Case studies have been classified according to their interpreted depositional environment and ordered according to their geological age (see Tables S1-5). For each case study examined here, data have been extracted on stratigraphic thickness, tectonic setting of the sedimentary basin and sedimentary architecture; these data are drawn from the original source works and related published literature. References to all considered literature data sources are provided in Supplementary Tables 1–5.

For all case studies deposited after 3.2 Ga, a classification of tectonic basin setting is provided. The tectonic basin setting is based on Kingston et al.,'s (1983a,b) classification scheme, as modified by Mitchell and Reading (1986) and Einsele (2000). Continental interior sag basins comprise epicontinental and intracratonic basins; continental interior fracture basins comprise grabens, rift valleys and aulacogens; subduction-related basins comprise fore-arc, back-arc and inter-arc basins; collision-related basins comprise remnant, peripheral and retroarc foreland, intramontane and intermontane basins; strike-slip/wrench basins comprise pull-apart and transpressional basins. The studied successions are classified according to the phase of cycles of supercontinent assembly, tenure and breakup during which they formed, categorized as: 'no known supercontinent', 'assembly phase', 'tenure phase', and 'breakup phase' (Table S6). The ages and phase of supercontinent assembly, tenure and breakup are interpreted from Young (2013), Nance et al. (2014) and Pesonen et al. (2021). All case studies of successions deposited prior to 3.2 Ga (Hadean, Eoarchean, and Paleoarchean) are not categorized according to the tectonic classification scheme because evidence with which to reach a consensus on plate tectonics for the early Earth is scant (e.g. Korenaga, 2013; François et al., 2022; Kusky et al., 2018; Cawood et al., 2018; Palin et al., 2020; Windley et al., 2021). Plate tectonics *sensu lato* is demonstrated to have begun in the Mesoarchean to early Paleoproterozoic (3.2–2.3 Ga), where early tectonic modes – stagnant or sluggish lid plate tectonics – operated; modern plate tectonics *sensu stricto* is unambiguously demonstrated from the Paleoproterozoic (2.2 Ga) onwards (Brown et al., 2020).

In this study, the thickness value reported for a case study reflects the maximum observed thickness of the stratigraphic unit. This methodology ensures consistency between measurements; however, it does not account for lateral variability in the thickness of a particular case-study succession and does not consider variability in data coverage and dimensionality.

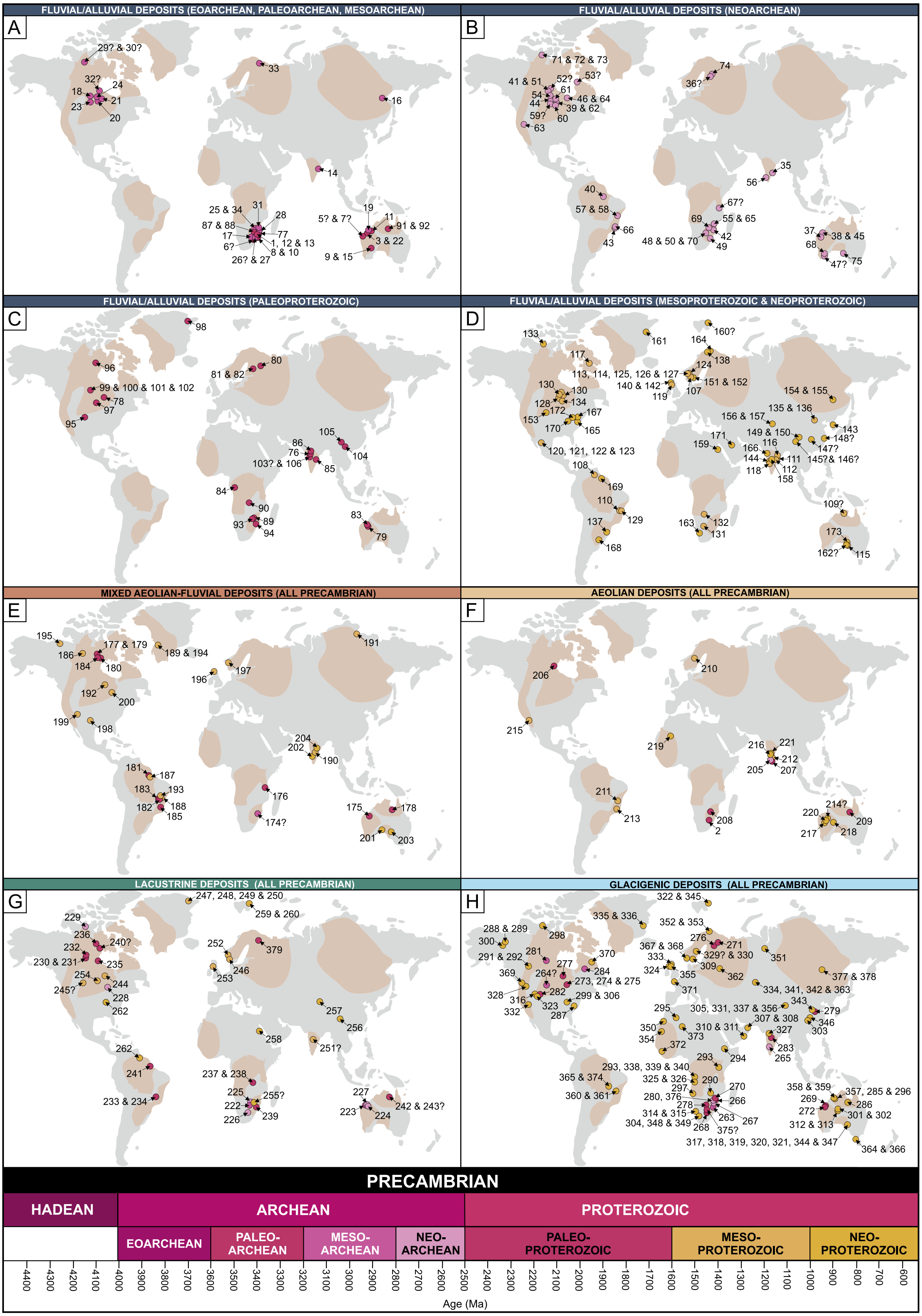

Fig. 1. Global maps showing the distribution of continental systems from the Eoarchean to the Neoproterozoic. The numbers of the case studies correspond with Supplementary Tables 1–5. The estimated extent of Precambrian cratonic regions are shaded in brown (modified after Bleeker, 2003).

3. Limitations

Studying the Precambrian rock record presents several challenges and limitations due to the extreme age of the rocks and the effects of geological processes that may have altered or destroyed much of the original evidence. Key limitations are as follows.

1) Age uncertainty. In the absence of volcanic tuff layers in sedimentary strata – which can be dated using traditional zircon U–Pb isotopes (e.g., Xiong et al., 2023) – absolute dating of Precambrian sedimentary successions can be problematic due to the general lack of material suitable for dating (e.g., Rodríguez-López et al., 2014). The absence of well-defined stratigraphic markers, such as distinctive fossils, in the Precambrian rock record makes it challenging to establish precise age correlations or construct detailed chronostratigraphic frameworks. However, given that cases studies are typically broadly assigned to geological periods (or parts thereof), this limitation is not a significant shortcoming.
2) Incomplete preservation and lack of well-preserved rocks. The Precambrian rock record is highly incomplete. Many of the rocks from this period have been subject to intense metamorphism, erosion, and subsequent tectonic activity, which can lead to the loss or alteration of original evidence. As a result, significant portions of the Precambrian record have been destroyed. The destruction of primary sedimentary fabric and structures that could otherwise have been used to accurately identify Precambrian sedimentary successions could lead to the omission of potential case studies. For example, some exposed Precambrian case studies may remain unrecognized, whereas others may have been erroneously misidentified as the products of different sedimentary environments in the wider literature; see Stewart (2002), Ielpi et al. (2016) and Lebeau and Ielpi (2017).
3) Lack of representative sampling. The Precambrian spans over 4 billion years. Thus, it is challenging to obtain a comprehensive and representative sampling of rocks from all periods within the Precambrian. Geological studies often rely on limited exposures, isolated outcrops, and sparse drill core samples, making it difficult to draw accurate conclusions about global geological processes and events. Moreover, there are geographical regions (e.g., western US) and age ranges (e.g., the part of the Neoproterozoic associated with Snowball Earth) which have been more extensively sampled for reasons of accessibility and popularity, else have been the focus of intensive study for longer times than other regions or intervals in the Precambrian. These factors increase both the number of publications and the number of depositional environments reported (i.e. the number of case studies). This leaves a key question open: does the existing scientific literature accurately reflect all aspects of Precambrian strata? Almost certainly not.
4) Interpretational challenges. The limited preservation and lack of well-preserved rocks from the Precambrian pose significant interpretational challenges. Researchers must rely on indirect evidence, such as isotopic ratios and geochemical signatures, to reconstruct past environments and processes. Interpreting these data can be complex and subject to multiple plausible explanations.
5) This study relies on the accurate interpretation of the palaeoenvironmental significance of outcropping Precambrian rocks by the authors in all original source works. Given the lack of well-preserved rock units, a given case study could potentially have more than one interpretation of its formative depositional environment. For example, some deposits have been alternatively interpreted as fluvial or marine in origin (e.g., Panorama Formation; Retallack, 2018). All case studies that have equivocal interpretations of their depositional environment are specified in the Supplementary Tables 1 - 5.
6) Extrapolations at larger scale of interpretations based on observations made at smaller scales are problematic, especially in relation to the analysis of thickness data. For example, in the literature, interpretations of facies associations indicative of sub-environments of deposition made at member level may be extrapolated to formation level without direct evidence. Thickness data are considered at the group or formation level where additional information is lacking. However, unrecognized intervening deposits of different origin may be present within a group or formation; thus, in such cases thickness data have limited value for scopes of comparison. Additionally, thickness data are typically derived from a specific outcrop or geographic location, and do not capture basin-wide variability in the thickness of a specific succession. In order to mitigate these issues, cumulative thicknesses are presented in Figs. 2 and 3, rather than absolute thicknesses.

Acknowledging the above limitations regarding the incompleteness of the Precambrian record and variability in data quality, the quantitative results presented below must be treated with a note of caution. Notwithstanding, this study has attempted to access and utilize a wide spectrum of published data to reveal useful conclusions from an imperfect but informative sedimentary record.

4. Results

Alluvial systems are documented from the Paleoarchean onwards (Fig. 2). With the exception of the Neoproterozoic, alluvial strata are the most abundant type of sedimentary deposits by both number of individual case studies (Fig. 2A) and cumulative thickness (Fig. 2B). In the eras of the Archean, alluvial systems account for 80 – 100 % of recorded case studies and 78 – 100 % of the total recorded lithology (Fig. 3). In the eras of the Proterozoic, alluvial systems account for between 25 and 49 % of recorded case studies and 43 – 69 % of the total recorded stratigraphy (Fig. 3). The greatest number of alluvial case studies are found in fracture- (32 %), collision-related (21 %) and subduction (20 %) basins (Fig. 4). Alluvial systems are most abundant in supercontinent assembly (30 %) and rift (37 %) phases (Fig. 5A).

Aeolian-alluvial and aeolian systems are first documented in the Meso- and Paleoarchean, respectively (Fig. 2). Aeolian-alluvial systems are most abundant in the Mesoproterozoic, forming 25 % of recorded case studies (Fig. 3A) and 25 % of the total recorded stratigraphy (Fig. 3B). Other than in the Neoproterozoic, systems of aeolian origin that lack alluvial interactions are consistently less abundant (Fig. 2A), and form less of the cumulative thickness (Fig. 2B), than mixed aeolian-alluvial systems. Numbers of aeolian case studies also peak in abundance in the Mesoproterozoic (Fig. 3A), forming 6 % of the cumulative stratigraphic thickness (Fig. 3B). The greatest proportion of aeolian-alluvial and aeolian case studies are from sag basins (aeolian-alluvial = 37 %; aeolian = 59 %; Fig. 4) and fracture basins (aeolian-alluvial = 50 %; aeolian = 35 %; Fig. 4). Mixed aeolian-alluvial and aeolian systems are most likely to be related to the supercontinent breakup phases (aeolian-alluvial = 32 %; aeolian = 39 %; Fig. 4).

Lacustrine deposits are documented from the Mesoarchean onwards (Fig. 2A-B). Recorded lacustrine case studies peak in the Paleo- and Mesoproterozoic, forming 19 % and 18 % of recorded case studies, respectively but form only 4 % and 2 % of the total cumulative thickness in these eras, respectively (Fig. 3). Lacustrine deposits have dominantly accumulated in continental interior fracture (51 %) basins (Fig. 4), and are in most part related to supercontinent assembly (42 %) and breakup (33 %) phases (Fig. 5). Generally, exorheic drainage patterns are the most common drainage type in the Precambrian lacustrine record (Fig. 6A). Exorheic lacustrine basins peak in abundance in the Mesoarchean and Mesoproterozoic, forming 100 % of recorded lacustrine basin types (Fig. 6A). Endorheic basins peak in abundance in the Neoarchean and Paleoproterozoic, forming 50 % and 47 % of recorded lacustrine basin types, respectively (Fig. 6A). In the Precambrian nonsaline lakes are generally the dominant lacustrine deposit (Fig. 6B); however, saline and partly arid lakes peak in abundance in the Neoarchean and Paleoproterozoic forming 50 % and 53 % of recorded

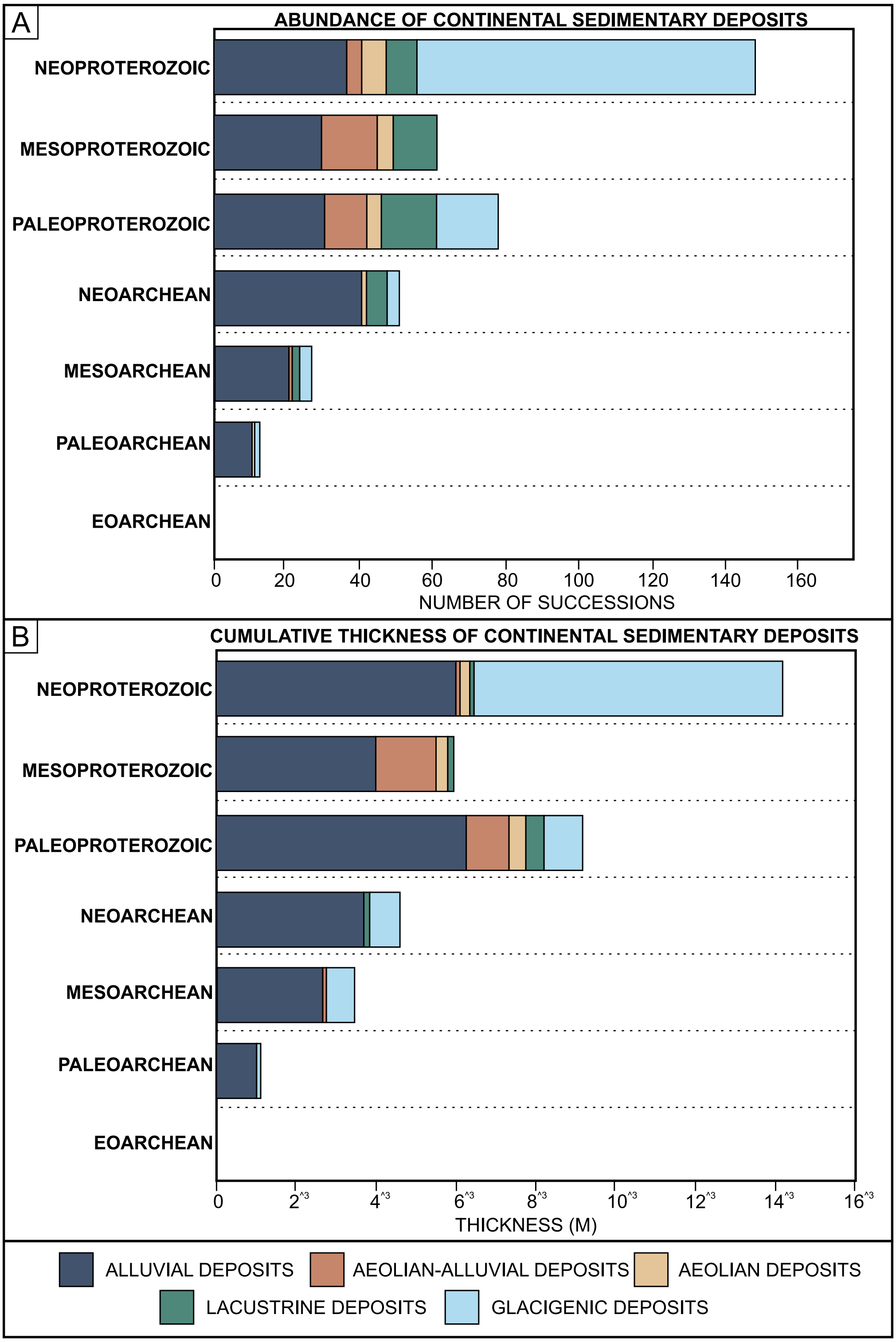

Fig. 2. A) Abundance of continental sedimentary deposits and B) thickness of continental deposits through geological time.

lacustrine deposits, respectively (Fig. 6B).

Glacigenic deposits are tentatively first documented in the Paleoarchean (Fig. 2). Glacigenic deposits are most widely documented in the Neoproterozoic, where they form 62 % of recorded case studies (Fig. 3A) and 54 % of the cumulative continental stratigraphy (Fig. 3B). Glacigenic deposits were most commonly accumulated in continental interior fracture basins (53 %), and at times of supercontinent breakup (75 %; Fig. 5).

The abundance of all continental deposits shows a general increase from the Archean towards the end of the Proterozoic ($R^2 = 0.4$; Fig. 7A). However, the abundance of continental deposits exhibits some cyclic variation through time. Peaks in the number of documented case studies occur at about 2,800 Ma, 1,800 Ma, 1,200 Ma and the period from 700 to 600 Ma (Fig. 7B).

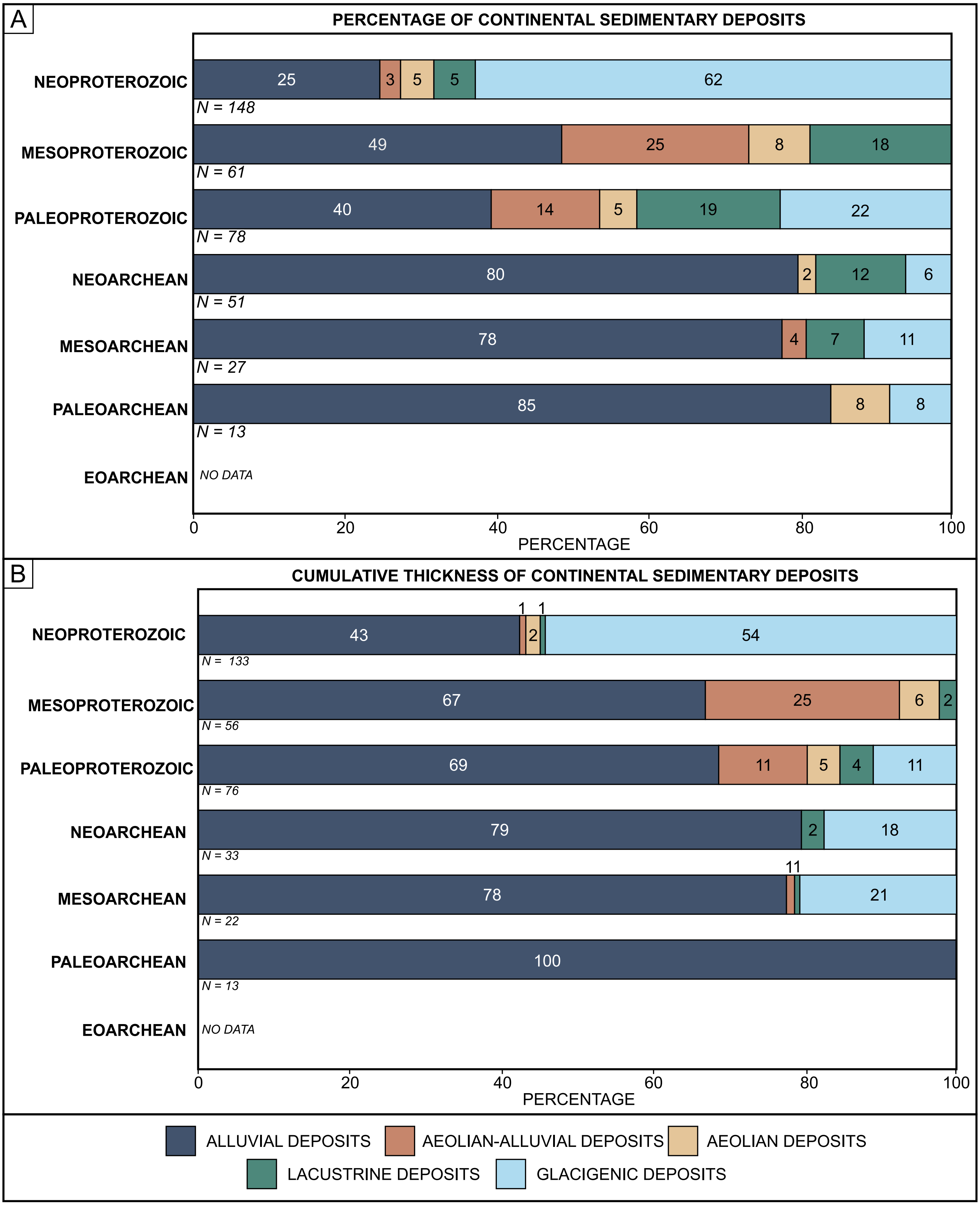

Fig. 3. A) Percentage of continental sedimentary deposits based on count of stratigraphic units and B) cumulative thickness of continental deposits through geological time.

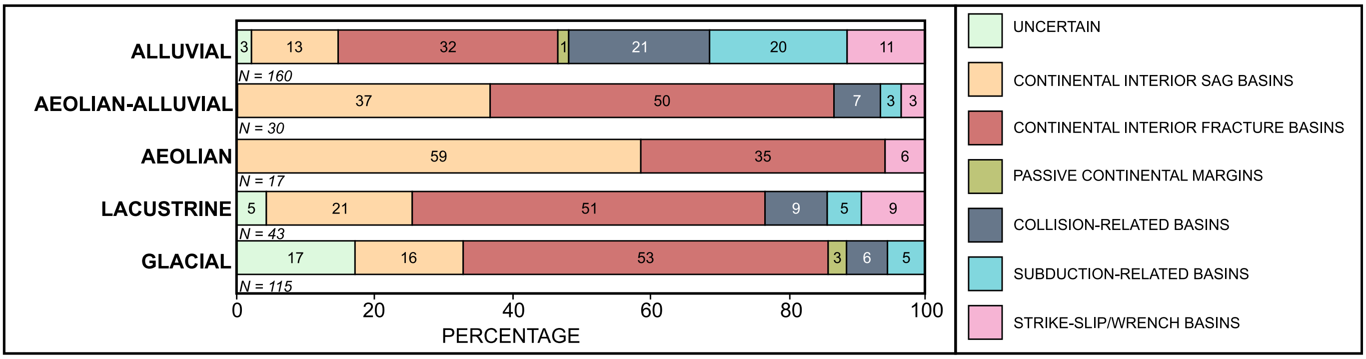

Fig. 4. Basin setting of continental deposits deposited after 3.2 Ga.

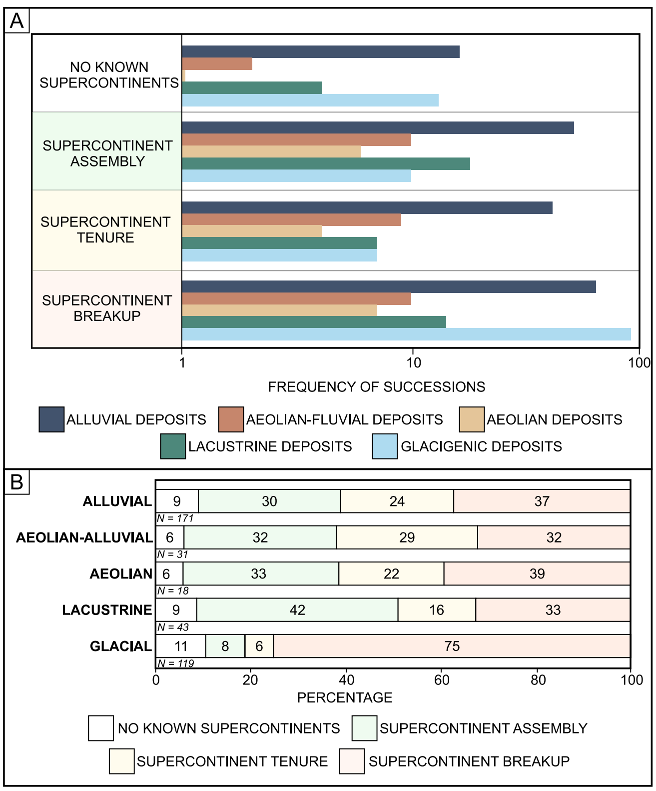

Fig. 5. A) Frequency of continental case studies deposited during different phases of the supercontinent cycle. B) Percentage of supercontinent phases associated with different depositional environments.

5. Discussion

5.1. Aeolian deposits

The oldest documented occurrence of wind-blown sediment is the Paleoarchean (ca. 3,280 Ma) Green Sandstone Bed (Mendon Formation, South Africa). However, Archean aeolian systems are exceedingly rare. The scarcity of aeolian systems in the Archean contrasts markedly with the abundance of alluvial successions (Fig. 8). Both mixed aeolian-alluvial and aeolian systems become more abundant at ca. 2.1 Ga. However, compared to alluvial systems, they remain relatively under-represented (Figs. 2, 3, 8). Potential explanations for the limited number of documented early Precambrian aeolian systems are discussed below.

5.1.1. Aeolian system development

The development (or lack thereof) of aeolian systems in the Precambrian has been widely debated (e.g., Eriksson et al., 2005; Bose et al., 2012); a variety of competing, or even contradictory, theories have been postulated (e.g., Tirsgaard, and Øxnevad, 1998; Bose et al., 2012; Lebeau and Lelpi, 2017; Goosman et al., 2018). Competing hypotheses primarily relate to prevailing palaeoclimate and atmospheric conditions during the early Precambrian. These are discussed below.

5.1.1.1. Precambrian atmospheric conditions. There is a general consensus that the early Earth had an atmosphere of some form, which arose from mantle outgassing and/or the melting of comets (Cloud, 1988). However, the density of the atmosphere in the early Precambrian remains highly contested (e.g., Som et al., 2012; Kavanagh and Goldblatt, 2015; Marty et al., 2013; Avice et al., 2018). Postulated early Precambrian atmospheric densities vary between less than half that of the present day (Som et al., 2016), no more than the present day (Marty et al., 2013; Avice et al., 2018), and up to ca. 10 times that of the present day (e.g., Kavanagh and Goldblatt, 2015). The lack of proxies for atmospheric pressure and density makes reliable inferences of these conditions challenging. The potential influence of relatively lighter and denser atmospheres on processes of aeolian transport are discussed next.

Wind-tunnel experiments indicate that extreme wind velocities would be required to entrain sand if the atmosphere was indeed significantly thinner than at present (e.g., Kok et al., 2012). For example, threshold velocities required to induce saltation vary between Earth and Mars; the latter has an atmosphere roughly 100 times less than that of the former. At the surface of the modern Earth, for an atmospheric density of 1.2 kg m^{-3}, the threshold velocity is ca. 0.2 m s^{-1}; at the surface of Mars, for an air density of 0.02 kg m^{-3}, the threshold velocity is ca. 1.5 m s^{-1} (Iversen and White, 1982; Kok et al., 2012). As such, under a relatively less dense atmosphere, the potential to construct aeolian bedforms would have been restricted to periods of extreme wind gustiness. A relatively less dense Precambrian atmosphere could potentially account for the dearth of Archean and early Paleoproterozoic aeolian deposits, which appears at odds with the high availability of sand due to high rates of continental weathering under a potentially hot and humid climate in the absence of vegetation (Donaldson et al., 2002; Ohmoto, 2004; Bose et al., 2012). The increased availability of sand that could be transported by the wind could then have favoured subsequent aeolian dune construction.

Notwithstanding, wind tunnel experiments indicate that, for a given speed, under lower atmospheric densities saltation height and length can increase once sand has been entrained; this effect is sometimes called long-hop saltation (Runyon et al., 2017). Long-hop saltation can facilitate the suspension and saltation of larger mean grain-sizes under high-speed wind gusts (Runyon et al., 2017). However, limited tests of early Precambrian aeolian deposits do not support statistically coarser-than-average grain sizes (Goosman et al., 2018). Moreover, widespread Mesoarchean alluvial deposits (Table S1; Figs. 2, 3 and 8) imply a

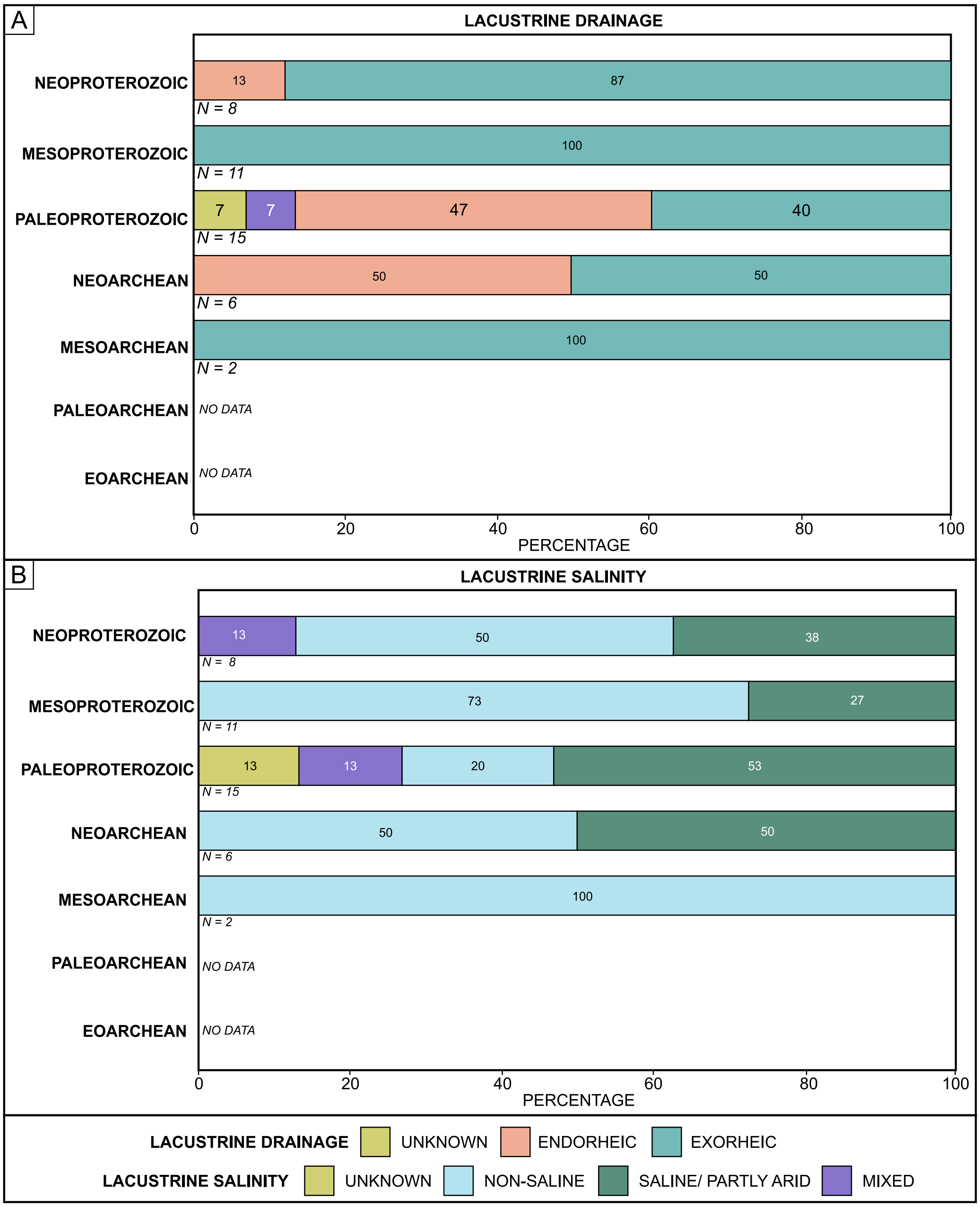

Fig. 6. Frequency of lacustrine case studies divided according to A) drainage patterns and B) salinity.

substantial hydrological cycle. This would require large amounts of precipitation recharging fluvial systems in adjacent highlands, which in turn would require a relatively thick atmosphere (Bose et al., 2012). Additionally, raindrop imprints preserved in thin tuffaceous layers within the Ventersdorp Supergroup (South Africa) indicate that an atmospheric density comparable to that of today had evolved by 2.7 Ga (van der Westhuizen et al., 1989). This suggests that a lighter early Precambrian atmosphere cannot fully account for the dearth of aeolian deposits prior to ca. 2.1 Ga.

Conversely, a denser and thicker Precambrian atmosphere (e.g., Kavanagh and Goldblatt, 2015) would have had significant consequences for aeolian transport processes. These include: 1) drag forces: the drag forces acting on particles suspended in the air would be increased, making their transport more difficult over long distances (cf. Smith, 1966). Aeolian transport would therefore be limited, and the range and extent of sediment transport would be reduced compared to what we observe in the present-day atmosphere. 2) Enhanced particle settling: with a denser atmosphere, particles would have a higher settling velocity due to increased air resistance. This means that once particles are lifted into the air, they would settle more quickly, reducing their potential for long-distance transport (cf. Bagnold, 1935; White, 1982). This settling would limit the size and distance of sediment deposits and contribute to localized accumulation near the source regions. 3) Limited saltation: saltation is the process of particles bouncing and hopping along the ground surface under the influence of wind (e.g., Anderson and Haff, 1988). In denser atmospheres, the increased air density would make it more challenging for particles to become entrained and initiate saltation. Consequently, the occurrence of saltation and the ability to transport larger particles would be reduced, affecting the size and distribution of aeolian deposits.

On Venus for example, the dense atmosphere (ca. 90 times denser than that of the Earth) causes low saltation thresholds, short saltation lengths, and relatively small incipient dunes (Kreslavsly and Bondarenko, 2017). Collectively, the aforementioned effects on aeolian

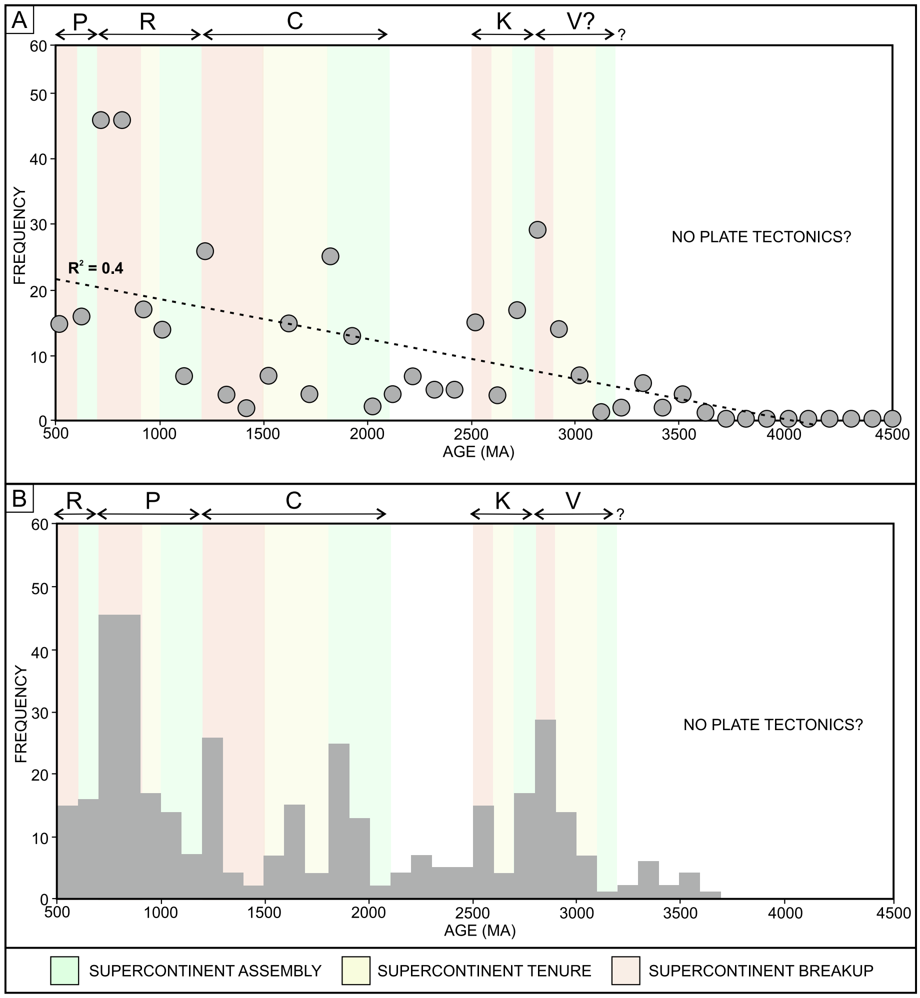

Fig. 7. A) Scatter and B) bar charts showing the abundance of all continental case studies through geological time. The letters and arrows at the top indicate the age range and name of proposed supercontinents. V = Vaalbaara; K = Kenorland; C = Columbia; R = Rodinia; P = Pannotia. The green, yellow and red colours indicate phases of the supercontinent cycle (assembly, tenure and breakup). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

transport would likely attenuate the formation of aeolian deposits in Archean and early Proterozoic. However, the exact conditions and dynamics of Precambrian atmospheres remain speculative and are still the subject of ongoing research and investigation. Specific effects on aeolian transport would depend on various additional factors, including wind velocities, sediment properties, and topographic features of the landscape.

5.1.1.2. Precambrian paleoclimates. The almost complete absence of Archean and early Paleoproterozoic aeolian strata has also been linked to the prevailing paleoclimate, which may have been warm and humid until ca. 2.3 Ga (e.g., Ohmoto, 2004). This potential humid setting may have inhibited the formation of aeolian deposits (Bose et al., 2012) such that extensive damp and wet substrates restricted the availability of dry sand for aeolian dune construction. However, other authors have suggested that aeolian processes would nevertheless have been able to operate under such potentially humid conditions due to the absence of stabilizing vegetation, which might otherwise have acted to bind and baffle sediment (e.g., Tirsgaard, and Øxnevad, 1998; Lebeau and Lelpi, 2017). Additionally, the lack of stabilizing vegetation may have made aeolian deposits more susceptible to post-depositional reworking by the wind, since vegetation can retard the re-suspension of sand and may act to protect dunes from erosion (Byrne and McCann, 1990; Ruz and Allard, 1994). However, this raises a further question: if aeolian deposits were more susceptible to wind erosion, should the reworking of aeolian deposits by the wind result in the formation of further aeolian deposits downwind? Again, the climatic conditions and lack of vegetation alone cannot fully account for the dearth of aeolian deposits.

5.1.1.3. Astronomical variability. The formation of Precambrian wind-blown deposits may have been influenced by aspects of astronomical variability: (1) the proximity of the Earth to the Moon; and (2) the rate of Earth's rotation. Definitive evidence for larger tidal ranges and faster rotation rates of Earth in the Precambrian, and the effects that these may have had on patterns of sedimentation, is lacking.

Williams (2000) used evidence obtained from tidal rhythmites to determine that the distance between the Earth and the Moon was 0.094 % and 0.035 % less than its current value at 2.45 Ga and 0.62 Ga, respectively. It has been postulated that the closer proximity of the Moon in the Precambrian may have resulted in stronger gravitational forces, leading to higher tides compared to the present day (Williams, 2000). The larger tidal range could have affected the exposure and availability of coastal sand for potential aeolian transport and deposition. Repeated marine wetting of large swathes of the coast and adjacent areas would inhibit the availability of dry sand for dune construction and destroy any incipient coastal dunes, or prevent their formation. However, other analyses of tidal rhythmites (e.g., Eriksson and Simpson, 2011) indicate that despite closer distances between the Earth and the

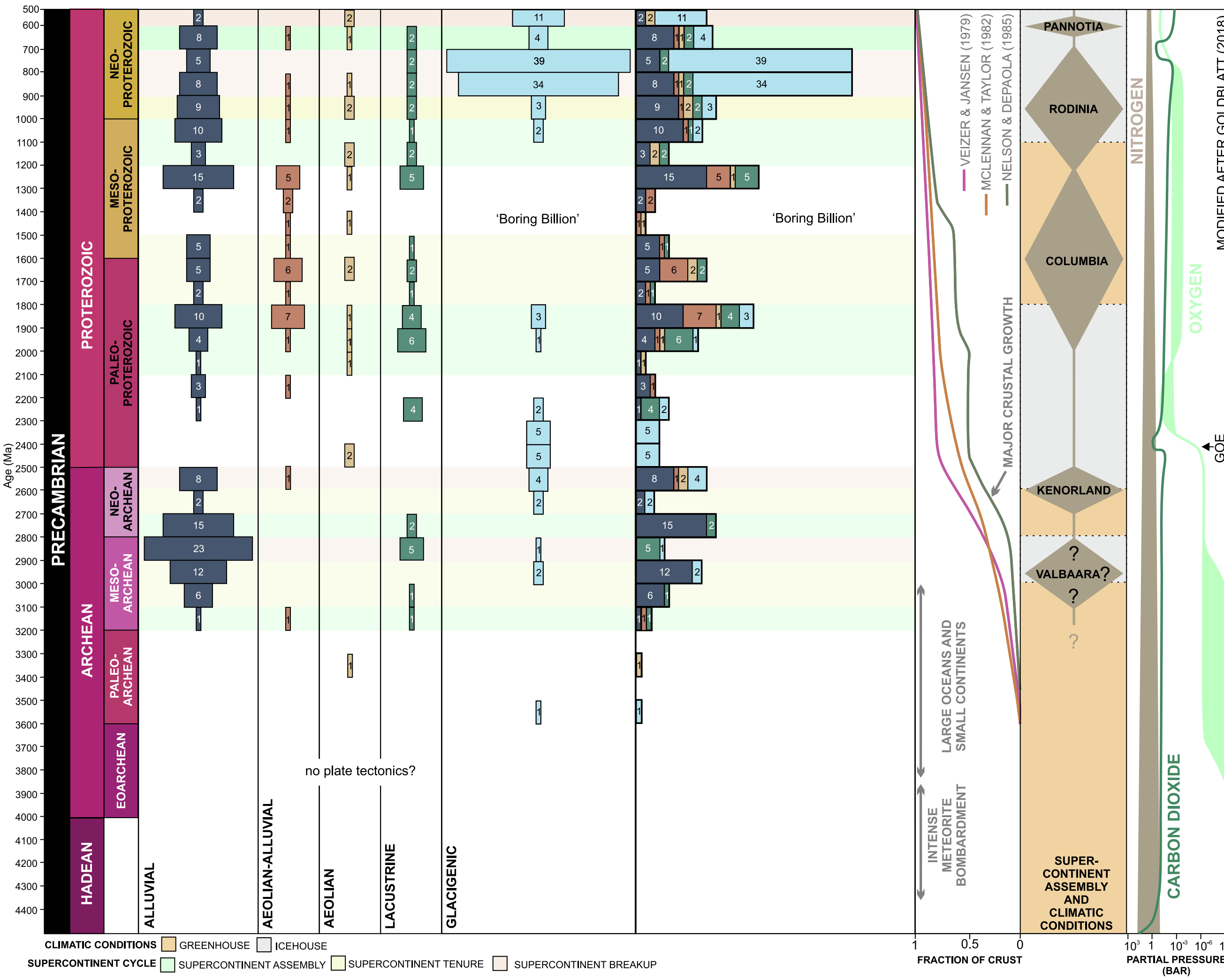

Fig. 8. A) Frequency of continental sedimentary systems through geological time, crustal growth models, supercontinent cycles, and paleoclimatic and atmospheric conditions. The frequency of fluvial, mixed aeolian-fluvial, aeolian, lacustrine and glacigenic case studies is represented by an appropriately coloured box; each box represents a 100 million year period; the number of case studies defined by that coloured box is written inside it. GOE = Great Oxidation Event.

Moon, bedforms were of a similar scale as present-day ones and extreme tidal ranges were unlikely in the Precambrian.

Additionally, in the Precambrian, the faster rotation rate of the Earth could have affected both patterns of atmospheric circulation and the global mean wind velocity. Modelling suggests that the rotation rate of the Earth has a profound effect on the general circulation of the atmosphere; faster rotation rates have been suggested to be associated with a greater number of Hadley cells compared to the present, resulting in a more complex atmospheric circulation pattern. This increased number of Hadley cells would have influenced wind patterns, affecting the distribution and transport of aeolian sediments across different regions. Additionally, modelling has indicated marked tropospheric latitudinal temperature gradients, a very narrow arid zone in the tropics, and a very dry and cold high-latitude region (Hunt, 1979). Given that modern aeolian systems are most likely to develop in the subtropics (Wilson, 1973), this effect may have spatially restricted the development of aeolian systems.

The faster rotation rate of the Earth in the Precambrian may have also increased the global mean wind velocities compared to today (Allen and Hoffman, 2005). Higher wind speeds would have potentially increased the erosive power and transport capacity of the wind. Stronger wind velocities increase the likelihood on entraining sand for the construction of aeolian dunes, but also increase the likelihood of existing dunes being extensively reworked. In the absence of stabilizing vegetation, the wind-driven deflation of aeolian dunes is likely to have been extensive. Again, this begs the question – what ultimately happened to this eroded sand if aeolian deposits were not permanently sequestered into the geological record? Ultimately, aeolian sand may have been sequestered in fluvial or marine environments. However, for the Precambrian record, data on sediment texture or microtexture that indicates preceding aeolian transport in other types of successions remains scant.

The extensive presence of microbial mats in terrestrial environments may have stabilized the sedimentary interface such that, even under higher velocity winds, the entrainment of sand was limited. In modern arid conditions, where the presence of vegetation is restricted, cryptobiotic films and crusts play a fundamental role in stabilizing surfaces and have been shown to increase resistance to wind erosion by up to four times, compared to non-stabilized surfaces (Belnap et al., 2001). Cryptobiotic films (such as microbial mats) may also protect previously accumulated aeolian deposits from wind reworking, and thus restrict sediment supply by limiting the chances of stored aeolian sands being recycles as time-lagged sediment sources for downwind aeolian accumulations (Basilici et al., 2020).

The implications of a closer Moon, faster rotation rate, and their effects on Precambrian aeolian deposits are still an area of ongoing research. The complex interactions between tides, atmospheric circulation, and sediment transport make it challenging to fully reconstruct the exact conditions and their consequences during that time.

Aeolian deposits only show a noteworthy increase in abundance at ca. 2.1 Ga, yet even this trend is restricted to mixed aeolian-alluvial systems (Fig. 8). This increase coincides with the global formation of 2.1 – 1.7 Ga orogenic systems, indicating substantial changes in paleogeography and growth of larger landmasses. However, the degree to which these orogenic systems were connected remains contested (Zhao et al., 2002, 2003; Meert and Santosh, 2017). Following this episode, the supercontinent of Columbia, which comprised almost all of the Earth's continental blocks, existed for approximately 300 million years (Huang and Li, 2023); the maximum extent of Columbia occurred at ca. 1500–1400 Ma (Meert and Santosh, 2017; Fig. 8).

The large continental interior of Columbia, parts of which were located at subtropical latitudes (Meert and Santosh, 2017), may have provided favourable conditions for the development of mixed aeolian and alluvial systems. This increase in aeolian-alluvial deposits also corresponds with a greenhouse phase (2.2 – 0.8 Ga; Fig. 8); greenhouse conditions have been shown to provide a greater chance of preserving thicker aeolian deposits relative to icehouse conditions (Cosgrove et al., 2021b).

5.1.2. Aeolian preservation

Generally, Precambrian aeolian systems that occur coeval with alluvial systems are more abundant, thicker and form a greater fraction of continental stratigraphy, compared to aeolian systems that develop without an alluvial influence (Figs. 2 & 3). This may reflect a preservational bias, such that aeolian-alluvial systems were more likely to be preserved in the long-term geological record. In this scenario, relatively high near-surface water-tables, recharged by incursions of alluvial systems into coeval aeolian environments, could increase the chances of preserving mixed aeolian-alluvial deposits. This is because the water table commonly defines the erosional baseline. Consequently, higher water tables could result in the rapid sequestration of aeolian deposits into the long-term geological record (Kocurek and Havholm, 1993). However, it can be envisaged that this effect would have likely been counteracted by the erosive power of non-vegetated alluvial systems; the lack of stabilizing vegetation would likely have made these systems highly sensitive to palaeoclimatic fluctuations, and prone to rapid channel migration and incursion into pre-existing aeolian systems (e.g. Eriksson and Simpson, 1998; Tirsgaard & Øxnevad, 1998). High-water tables associated with shorelines and low-energy transgressive shorelines may have drowned aeolian deposits. In Proterozoic coastal aeolian systems, marine reworking of aeolian deposits was also widespread, for example in the Whitworth Formation, Australia (Simpson and Eriksson, 1993) and the Venkatpur Sandstone, India (Chakraborty, 1991).

The most likely explanation for the preferential association of coeval aeolian-alluvial systems is the absence of vegetation during the Precambrian. Under these conditions, the following can be inferred: i) braided alluvial systems were more common across a variety of palaeoclimatic regimes (Long, 2019); and ii) aeolian processes of erosion, transport and deposition were more active, even under markedly more humid climates (Eriksson and Simpson, 1998; Tirsgaard & Øxnevad, 1998). Collectively, these effects would result in a greater overlap of depositional environments and more likely interactions between aeolian and alluvial systems. The presence of microbial mats may also have influenced aeolian-fluvial interactions through their capacity to retain water (Perillo et al., 2019), even in arid environments. This water retention may have enhanced fluvial processes by providing a localized water source for fluvial runoff, perhaps enhancing aeolian-alluvial interactions.

Both aeolian and mixed aeolian-alluvial deposits are most likely to be preserved in continental interior sag (i.e. intracratonic) and fracture (i.e. rift) basins (Fig. 3). Interior sag basins may have provided favourable conditions for aeolian preservation, such that accumulated aeolian deposits were sequestered into tectonically stable interior basins that experienced gradual, but long-lived, subsidence and sedimentary accumulation. The deep burial of aeolian deposits and the lack of extensive post-depositional erosion until much later in geological time (in many cases in the Phanerozoic; e.g., McArthur Basin, Australia; Vindhyan Basin, India) increased the preservation potential of aeolian deposits in these settings. Fracture basins, associated with the fragmentation of supercontinents, represent favourable settings for the development and preservation of aeolian deposits.

Due to the topographic funneling of winds through the high-sided walls of rift basins – which can channel and accelerate airflow through the basin – dunes can easily accumulate along the margin of rifts Additionally, as rift basins are amongst the most rapidly subsiding basins (Xie and Heller, 2009), aeolian deposits may have been rapidly sequestered beneath the erosional baseline (commonly defined by the level of the water table), thereby increasing their chance of long-term preservation in the geological record (Kocurek and Havholm, 1993; Cosgrove et al., 2023). In the Precambrian, there are multiple episodes of continental rifting associated with the break-up of supercontinents (Kenorland, Rodinia, Columbia; Young, 2013; Fig. 6). In non-rifting phases, or during hiatuses in accommodation generation, aeolian systems may have been present, but these systems may have had a lower preservation potential.

5.1.3. Misidentification of aeolian deposits

Typically, unambiguous identification of aeolian deposits in the geological record relies on observations of inversely graded wind-ripple, grainfall, grainflow and adhesion strata in fine to medium sandstone. These recognition criteria are supported by: 1) the identification of decimetre or larger-scale sets of cross-beds. 2) Foresets inclined at the angle of repose for dry sand (accounting for the effects of sediment compaction). 3) The geometry of depositional units, for example where inclined strata grade laterally into a plinth deposit (e.g. Hunter, 1977; Kocurek and Dott, 1981; Eriksson and Simpson, 1998). 4) Characteristic lateral and vertical facies associations. 5) Micro-scale criteria of characteristic grain size, composition, sorting and roundness. However, intense diagenesis, deformation and metamorphism acted to destroy many diagnostic aeolian structures and textures in Precambrian aeolian deposits, given their great age (Eriksson and Simpson, 1998; Simpson et al., 2012; Basilici et al., 2021). Precambrian aeolian deposits also tend to be associated with an abundance of sandsheet deposits, which are generally coarser-grained than their Phanerozoic counterparts (e.g. Biswas, 2005; Cosgrove et al., 2022). For these reasons, some instances of what are now widely considered to be Precambrian aeolian deposits have been previously misidentified as sheet-like alluvial bodies or shoreface marine deposits (e.g. Stewart, 2002; Lebeau and Ielpi, 2017). It is possible that a significant part of the Precambrian aeolian record remains misinterpreted.

5.2. Alluvial deposits

The majority of alluvial successions are interpreted to be the deposits of alluvial fans (both debris-flow and streamflow dominated), gravel- and sand-bed braided rivers, and non-confined sheet-like systems (Table S3). A broad consensus on fluvial systems of Precambrian age is that they were in many cases – but not always – characterized by: 1) broad channel systems occupying large braidplains. 2) Heightened rates of channel migration, relative to channel size. 3) Flashy surface runoff and high discharge rates. 4) A bedload-dominated character. 5) Limited bank stability and cohesion due to relatively reduced clay production and scant soil development arising from the lack of vegetation (e.g., Cotter, 1978; Eriksson et al., 1998; Smith, 1998). These characteristics may have made Precambrian rivers sensitive to changes in palaeoclimate and allowed braided fluvial systems to operate under a wider range of climatic conditions compared to modern and Phanerozoic systems (Tirsgaard and Øxnevad, 1998; Bose et al., 2012; Long, 2019). The relatively broad palaeoclimatic distribution of braided fluvial systems may partly account for the abundance of alluvial systems in the

Precambrian (Long, 2019).

In the Mesoarchean and Neoarchean the inferred presence of high-gradient alluvial-fan deposits and low-sinuosity river deposits in greenstone belts (e.g., Windley, 1995; Eriksson et al., 2007; Fedo et al., 2001) has been linked by some authors to the onset of Eoarchean plate tectonics (Windley et al., 2021). However, even in the absence of plate tectonics – which other authors considered to have started after 3.2 Ga (e.g., Brown et al., 2020) – gravitational mass-wasting depositional and erosional processes could have played a role in shaping the landscape (Leeder, 2011). While large-scale plate tectonics may not have been operating, localized tectonic activity (e.g., relative uplift and subsidence) could have been present during the Precambrian (Cawood et al., 2018). Faulting, subsidence, and uplift associated with intracontinental or local tectonic events could have created basins and mountainous regions, providing the necessary conditions for alluvial-fan formation.

Post 3.2 Ga, alluvial systems were common across all phases of the supercontinental cycle, but their development peaked during supercontinent assembly (Figs. 7 & 8), where they were more widespread than all other continental depositional systems (Fig. 5). Alluvial sedimentation may have been enhanced during times of supercontinent assembly due to the genesis of major active mountain belts from which alluvial systems could develop. The basin setting of alluvial systems is notable; unlike all other continental deposits, alluvial systems are commonly found as part of the fills of collision- and subduction-related basins (Fig. 4). The thickness of these successions may reflect rapid sediment shedding from orogenic belts, in combination with generally high rates of subsidence and accommodation generation in these basin settings (Einsele, 2000; Cosgrove et al., 2023).

Alluvial successions were also extensively deposited during phases of supercontinent tenure (Fig. 5A). This phase of the supercontinent cycle may have promoted the formation of large drainage areas extending from supercontinent interiors to coastlines, leading to the formation of alluvial systems larger than any documented today – a time of disassembled continents and sea-level highstand. This is supported by the dominance of exorheic lacustrine drainage systems (Fig. 6A), suggesting the prevalence of open systems in which surface waters ultimately drained to the ocean (Williams and Mann, 2022). The peak in exorheic lacustrine drainage systems occurs in the Mesoproterozoic; the early Mesoproterozoic overlaps with the tenure phase of the largest Precambrian supercontinent – Columbia.

5.3. Lacustrine deposits

The relative rarity of lacustrine deposits in the Precambrian may be partly explained by the difficulty of recognizing them. Lacustrine deposits may be unrecognized or misidentified for a number of reasons. In the Phanerozoic record, lacustrine deposits typically contain fossils of freshwater organisms such as algae, molluscs, and fish (e.g, Park and Gierlowski-Kordesch, 2007). However, the absence of fossils of complex lifeforms in the Precambrian makes it harder to confirm the lacustrine origin of certain deposits. In the Phanerozoic, the presence of lacustrine evaporites (e.g. Eugster, 1980) can be used, where relevant, as a diagnostic criterion for lacustrine deposits. However, identification of evaporitic Precambrian lacustrine deposits is more challenging, since evaporites are commonly pseudomorphic and thus are poor diagnostic indicators of environment of origin (Donnelly and Crick, 1988). In some cases, ancient lacustrine deposits can resemble analogous shallow-marine deposits; without clear evidence of freshwater fauna and flora, it can be challenging to distinguish between lacustrine and marine sediments (e.g., Picard and High, 1972). This is because sedimentary cyclicity common to lacustrine sediments is also found in many marine mesosequences (Friedman et al., 1992) and stromatolites occur in the deposits of both environments (e.g., Hoffman, 1976; Fedorchuk et al., 2016). Also, modern lakes can provide valuable insights into the formation of lacustrine deposits, but the conditions of Precambrian lakes may have been significantly different from those of modern lakes (e.g., Swanner et al., 2020). This lack of modern analogues makes it challenging to interpret ancient lacustrine environments accurately.

From the Middle Paleoproterozoic onwards, lacustrine successions show a relative increase in abundance (Fig. 8). Precambrian lacustrine deposits are most common in continental fracture basins (rift basins). In simple terms, the stretching and thinning of the lithosphere, leading to subsidence of the crust in the rift basin, are likely to have created large depressions in which water could accumulate to form a lake. As the rift basin continues to subside over time, the depth and size of the lake may increase; many additional factors may however determine whether a lake is ultimately formed, including subsidence rate and rates or sediment supply, amongst others. Rifting can impact groundwater flow patterns, such that faults and fractures associated with the rift provide pathways for groundwater to accumulate and contribute to the formation of lakes. Rift shoulders may have also influenced the meteorological cycle, creating a rain-shadow effect, providing rainfall that would ultimately recharge the groundwater, flooding the rift valley to form a lake.

The formation of large continents in the Precambrian is also likely to have had significant impacts on the drainage of lake systems. Supercontinent building is likely to have generated closed-interior basins with endorheic internal drainage; Precambrian lacustrine systems show maximum recorded endorheic lacustrine systems associated with the formation of Kenorland (Neoarchean) and the assembly and tenure of Columbia (Paleoproterozoic; Figs. 7 & 9).

Moreover, in the Paleoproterozoic, lakes associated with saline or partly arid conditions are the dominant lake type (Fig. 6B). This trend is coincident with an increase in aeolian and mixed aeolian-alluvial deposits (Fig. 3) and may reflect the establishment of desertic conditions in the continental interior of Columbia (Young, 2013). However, this observation is caveated by the fact that partly arid or saline lakes in the Precambrian record are relatively easier to identify compared to hydrologically open and more permanent lakes (e.g. Unrug, 1984; Eriksson et al., 2004).

5.4. Glacial deposits

There is a necessary temporal control on the occurrence of glacial deposits (e.g. Young, 2004; Fig. 8). Archean glacial deposits are recorded from the Pongola Supergroup (e.g. Young et al., 1998) and in the Witwatersrand Basin (e.g., Wiebols, 1955; Harland, 1981; Crowell, 1983); putative glacial deposits are also documented in Montana (USA; e.g. Page and Koski, 1973), Southern India and elsewhere (Supplementary Table S5), but their origin is ambiguous and has been contested. The lack of Archean glacial deposits is curious given that the solar radiance may have been ca. 25–20 % less than at present. However, the atmosphere was high in carbon dioxide and methane; the former at ca. 10 to 2,500 times greater than present concentrations, and the latter at 10^2 —10^4 times greater than present concentrations (Catling and Zahnle, 2020). Therefore, the atmosphere would have retained a high proportion of radiative energy (Young, 2018). The lack of glacial deposits from the Eo- and Paleoarchean may reflect higher surface temperatures, due to the high atmospheric greenhouse gas content (Fig. 8; Young, 2018). Alternatively, the lack of evidence for early Archean glaciations in the geological record may reflect the scarcity of continental lithosphere that could have housed glacigenic deposits on a frozen water-covered planet (Young, 2018). Alternatively, considering the vastness of Archean time and paucity of suitably preserved strata, the paucity of glacigenic deposits of this age may simply reflect a lack of preservation.

The first widespread glacioera occurred at ca. 2.5 – 2.2 Ga (Huronian Glaciation; Fralick and Miall, 1989). The Huronian glaciation occurred in broad temporal proximity with the Great Oxidation Event (GOE; Goldblatt et al., 2006), where increased atmospheric oxygen caused a concomitant decrease in levels of atmospheric methane (Goldblatt et al., 2006). This resulted in a decrease in the greenhouse effect, causing net global cooling (Kopp et al., 2005; Kasting and Howard, 2006; Goldblatt et al., 2006). The Huronian Glaciation occurs coeval with documented occurrences of platform carbonates and Banded Iron Formations (BIF), which accumulated on several cratons (Young, 2018). This trend may have arisen because of Neoarchean crustal growth (e.g. Veizer and Jansen, 1979; McLennan and Taylor, 1982; Nelson and DePaolo, 1985; Fig. 8), when rapid expansion of mid-ocean ridges and the formation of emergent cratons caused eustatic sea-level rise (Eriksson et al., 2001). However, given that Neoarchean crustal growth peaked at ca. 2.7 Ga, this may not have had a bearing on sea level at ca. 2.5 Ga.

The period between 1.8 Ga and 800 Ma is informally known as the 'boring billion' (Holland, 2006), because there is little evidence of glacial activity and a perceived paucity of significant global change overall (Fig. 8). The glacigenic deposits that do exist are mainly glacio-alluvial and periglacial in origin (Young, 2018; Table S5). Glacigenic deposits peak in frequency and cumulative thickness in the Neoproterozoic. Typically, three widespread glacial episodes are documented in the Neoproterozoic: the Sturtian (717 – 659 Ma), Marinoan (640 – 635 Ma) and Gaskiers glaciations (579 Ma; Young, 2018). These Cryogenian glaciations are associated with extreme glaciation and extensive ice cover down to sea level in tropical latitudes; two theories have been proposed: the Snowball Earth hypothesis (cf. Kirschvink, 1992) and the high obliquity theory (cf. Williams, 1975). The former advocates that glaciers spread from polar to equatorial regions, whereas the latter advocates that glaciers only developed in relatively low-latitude regions, which would have experienced a tropical climate at other times, due to the high obliquity of the Earth; for a summary of these hypotheses see Young (2018). At this time, the radiative power of the sun was ca. 6 % less than at present (Feulner, 2012). However, decreased solar luminosity cannot account for the Neoproterozoic glaciations alone: during earlier periods of Earth history, solar luminosity was relatively lower, yet no glaciation is documented (Fig. 8; Eyles and Januszczak, 2004).

It has been postulated that cycles of supercontinent assembly and break-up during the Precambrian acted as drivers of glacigenic activity, such that glacigenic deposits tended to accumulate in supercontinental breakup phases (Fig. 5). Proposed models suggest that during these phases of supercontinent breakup, enhanced chemical weathering of uplifted rift shoulders, orogenic belts and new continental margins led to the sequestration of carbon dioxide and consequent climate cooling and glaciation (Hoffman and Schrag, 2002; Eyles and Januszczak, 2004). The data presented here indicate that glacial deposits were most likely to be deposited in continental fracture (i.e. rift) basins (Fig. 4), and that glacial deposits are preferentially found in the breakup phase of the supercontinental cycle (Figs. 6 & 9).

5.5. *Continental record of Earth surface processes*

Patterns of continental sedimentation may be related to crustal evolution, through its direct impact on Earth surface processes (Eriksson et al., 2001). As the evolution of the Precambrian crust progressed, possible source terrains for clastic sediment would have evolved through time. As with many aspects of Precambrian geology, models of crustal evolution remain equivocal; a variety of different models describing crustal evolution have been proposed, which exhibit considerable diversity (e.g., Veizer and Jansen, 1979; McLennan and Taylor, 1982; Nelson and DePaolo, 1985; Bleeker, 2003; Percival et al., 2012; Stern et al., 2016; Cawood et al., 2018; Dhuime et al., 2018; Hawkesworth and Brown, 2018; Hawkesworth et al., 2018, 2020, amongst many others).

A brief synthesis of crustal evolution and plate tectonics, which reflects the current literature is presented below. However, this topic remains highly debated in the literature. During the Hadean Eon (>4.0 Ga) Earth's surface was associated with intense volcanic activity, frequent meteorite impacts, and a largely molten or partially molten crust. There is limited direct geological evidence from this period, but it is believed that the earliest continental crust began to form, albeit in small, isolated patches (e.g., Harrison, 2009). The Archean Eon (4.0 – 2.5 Ga) saw significant progress in the formation of continental crust, likely through volcanic and tectonic processes. Evidence suggests that small continental landmasses, known as proto-continents, started to emerge during this time (e.g., Laurent et al., 2014). Plate tectonic processes, if they operated at all, may have been in an early or transitional stage, with some evidence pointing to subduction-like processes (e.g., de Wit, 1998; Komiya et al., 1999; Kusky et al., 2001; Moyen and Hunen, 2012). The Proterozoic Eon (2.5 – 0.54 Ga) witnessed the continued growth and amalgamation of continental landmasses, leading to the formation of larger continental blocks and proto-supercontinents (e.g., Zhao et al., 2003; Scotese, 2009). Evidence for the emergence of modern-style plate tectonics becomes more pronounced during this eon, including the presence of ophiolite complexes (e.g., Huang et al., 2021).

Conditions on early Earth may have not been favourable for the development of continental deposits: intense meteorite bombardment took place prior to 3.9 Ga, whereas during 3.9 – 3.0 Ga large oceans and small (<5%) portions of continental crust existed across the Earth's surface (Eriksson and Simpson, 1998; Fig. 8). The first peak in the abundance of continental deposits at 2.8 Ga occurs prior to the major postulated phase of crustal growth at 2.5 Ga, and broadly coincides with the stabilization of the hypothetical Valbaaran supercontinent (Zegers et al., 1998). However, geochronological and paleomagnetic uncertainties have led to yet unresolved debate about the timing, configuration – and even the existence – of Vaalbara (Evans et al., 2017; de Kock et al., 2021).

From the Proterozoic onwards, the development of stable cratons would have resulted in more conducive conditions for the preservation of continental deposits (Eriksson et al., 2005; Bose et al., 2012). Peaks in numbers of identified case-study successions of known ages vary (quasi-) periodically on a timescale of ~ 700–500 million years (Figs. 8 & 9). This variation coincides with the cycles of supercontinent assembly and disassembly (Pesonen et al., 2021); the supercontinent cycle is in turn intimately linked with whole mantle convection (Young, 2013; Nance et al., 2014; Pesonen et al., 2021). Thus, the evolution of Precambrian continental landscapes recorded in sedimentary successions chimes with evidence on supercontinent cyclicity resulting from multidisciplinary observations from geophysics (palaeomagnetism, heat flow, and seismology), palaeogeography and palaeontology (matching continental borders, stratigraphic sections, and fossil assemblages), stratigraphy, geochronology, and geochemistry (Young, 2013; Nance et al., 2014; Pesonen et al., 2021).

6. Conclusions

This study presents the first quantitative global assessment of the Precambrian continental sedimentary record, and ties the frequency, thickness and basin setting of these deposits to global events in the Earth's geosphere, biosphere and atmosphere. The examined Precambrian sedimentary record provides an insight into the surface processes shaping the early Earth. The vegetation-free Precambrian led to the widespread development of laterally extensive alluvial systems, which were present in a wide variety of palaeoclimatic regimes during supercontinent assembly and tenure. Aeolian and lacustrine systems are rarely recognized in the continental stratigraphic record, in part perhaps because of the challenges of accurately identifying these deposit types in very ancient successions. However, successions of saline and partly arid lakes and of mixed aeolian-alluvial systems increase in abundance at the time of formation of greenhouse desertic conditions in the continental interior of Columbia. Aeolian systems are preferentially preserved in fracture basins following the breakup of Columbia but remain relatively rare overall, likely due to aeolian deflation and reworking by alluvial and marine agents, in the absence of vegetation. The timing of deposition of glacigenic deposits coincides with phases of supercontinent breakup, when enhanced weathering of uplifted rift shoulders may have caused the sequestration of carbon dioxide, driving global atmospheric cooling. Overall, instances of continental deposits increase in number towards the Precambrian-Phanerozoic border. However, the abundance of continental deposits varies over quasi-periodic cycles of 500 – 700 million years, coinciding with the tenure and breakup of Precambrian supercontinents.

CRediT authorship contribution statement

Grace I.E. Cosgrove: Conceptualization, Methodology, Software, Formal analysis, Data curation, Writing – original draft, Visualization. **Luca Colombera:** Methodology, Software, Writing – review & editing. **Nigel P. Mountney:** Methodology, Writing – review & editing, Supervision, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data is included in the Supplementary Tables

Acknowledgements

We thank the sponsors and partners of the Fluvial, Eolian & Shallow-Marine Research Group (FRG-ERG-SMRG) of the School of Earth and Environment at the University of Leeds (UK) for financial support for this research. We would also like to thank reviewers Alex Hoffmann and Ed Simpson, and Editor Frances Westall for their valuable advice, which has greatly improved this manuscript.

Appendix A. Supplementary data

1. Table S1: List of Precambrian alluvial systems. Question marks (?) indicate unknown or uncertain data entry. 2. Table S2: List of Precambrian mixed aeolian-alluvial systems. Question marks (?) indicate unknown or uncertain data entry. 3. Table S3: List of Precambrian aeolian systems. Question marks (?) indicate unknown or uncertain data entry. 4. Table S4: List of Precambrian lacustrine systems. Question marks (?) indicate unknown or uncertain data entry. 5. Table S5: List of Precambrian glacigenic systems. Question marks (?) indicate unknown or uncertain data entry. 6. Table S6: Phases of cycles of supercontinent assembly, tenure and breakup are denoted as follows: 0 = no known supercontinent; 1 = assembly phase; 2 = tenure phase; 3 = breakup phase. The ages and phase of supercontinent assembly, tenure and breakup are interpreted from Young (2013); Nance et al. (2014); Pesonen et al. (2021). Supplementary data to this article can be found online at https://doi.org/10.1016/j.precamres.2023.107286.

References

Allen, P.A., Hoffman, P.F., 2005. Extreme winds and waves in the aftermath of a Neoproterozoic glaciation. Nature 433, 123–127.

Anderson, R.S., Haff, P.K., 1988. Simulation of Eolian Saltation. Science 241, 820–823. https://doi.org/10.1126/science.241.4867.820.

Avice, G., Marty, B., Burgess, R., Hofmann, A., Philippot, P., Zahnle, K., Zakharov, D., 2018. Evolution of atmospheric xenon and other noble gases inferred from Archean to Paleoproterozoic rocks. Geochim. Cosmochim. Acta 232, 82–100. https://doi.org/10.1016/j.gca.2018.04.018.

Bagnold, R.A., 1935. The movement of desert sand. Geogr. J. 85, 342–365.

Bállico, M.B., Scherer, C.M.S., Mountney, N.P., Souza, E.G., Reis, A.D., Gabaglia, G.R., Magalhães, A.J.C., 2017. Sedimentary cycles in a Mesoproterozoic aeolian erg-margin succession: Mangabeira Formation, Espinhaço Supergroup. Brazil. Sed. Geol. 349, 1–14.

Basilici, G., Soares, M.V.T., Mountney, N.P., Colombera, L., 2020. Microbial influence on the accumulation of Neoproterozoic aeolian-dominated depositional systems: Venkatpur Sandstone Formation, Telangana State, southern India. Precam. Res. 347, 105854 https://doi.org/10.1016/j.precamres.2020.105854.

Basilici, G., Mesquita, A.F., Soares, A.V.T., Janočko, J., Mountney, N.P., Colombera, L., 2021. A Mesoproterozoic hybrid dry-wet aeolian system: Galho do Miguel Formation. SE Brazil. Precam. Res. 359, 106216 https://doi.org/10.1016/j.precamres.2021.106216.

Belnap, J., Budel, B., Lange, O.L., 2001. Biological soil crusts: characteristics and distribution. In: Belnap, J., J., Lange, O.L (Eds.), Biological Soil Crusts: Structure, Function, and Management. Springer-Verlag, Berlin, pp. 3–30.

Biswas, A., 2005. Coarse aeolianites: sand sheets and zibar-interzibar facies from the Mesoproterozoic Cuddapah Basin. India. Sed. Geol. 174, 149–160.

Bleeker, W., 2003. The late Archean record: a puzzle in ca. 35 pieces. Lithos 71, 99–134. https://doi.org/10.1016/j.lithos.2003.07.003.

Bose, P.K., Eriksson, P.G., Sarkar, S., Wright, D.T., Samanta, P., Mukhopadhyay, S., Mandal, S., Banerjee, S., Altermann, W., 2012. Sedimentation patterns during the Precambrian: a unique record? Mar. Pet. Geol. 33, 34–68. https://doi.org/10.1016/j.marpetgeo.2010.11.002.

Brown, M., Johnson, T., Gardiner, N.J., 2020. Plate Tectonics and the Archean Earth. Annual Review of Earth and Planetary Sciences 48, 291–320. https://doi.org/10.1146/annurev-earth-081619-052705.

Byrne, M.L., McCann, S.B., 1990. Stratification and sedimentation in complex vegetated coastal dunes, Sable Island, Nova Scotia. Sedimentary Geology 66, 165–179.

Catling, D.C., Zahnle, K.J., 2020. The Archean atmosphere. Sci. Adv. 9 https://doi.org/10.1126/sciadv.aax1420.

Cawood, P.A., Hawkesworth, C.J., Pisarevsky, S.A., Dhuime, B., Capitanio, F.A., Nebel, O., 2018. Geological archive of the onset of plate tectonics. Phil. Trans. R. Soc. A 376 (20170), 405. https://doi.org/10.1098/rsta.2017.0405.

Chakraborty, T., 1991. Sedimentology of a Proterozoic erg: the Venkatpur Sandstone, Pranhita-Godavari Valley, South-India. Sedimentology 38, 301–322.

Cloud, P., 1988. Oasis in Space — Earth History from the Beginning. Norton, New York, W.W, p. 508.

Cosgrove, G.I.E., Colombera, L., Mountney, N.P., 2021b. Quantitative analysis of the sedimentary architecture of eolian successions developed under icehouse and greenhouse climatic conditions. GSA Bull. 133, 2625–2644. https://doi.org/10.1130/B35918.1.

Cosgrove, G.I.E., Colombera, L., Mountney, N.P., 2022. Eolian stratigraphic record of environmental change through geological time. Geology 50, 289–294. https://doi.org/10.1130/G49474.1.

Cosgrove, G.I.E., Colombera, L., Mountney, N.P., 2023. Quantitative analysis of aeolian stratigraphic architectures preserved in different tectonic settings. Ear. Sci. Rev. 237, 104293.

Cotter, E., 1978. The evolution of fluvial style, with special reference to the central Appalachian palaeozoic. In: Miall, A.D. (Ed.), Fluvial Sedimentology, Canadian Society of Petroleum Geologists Memoir, 5, 361-383.

Crowell, J.C., 1983. Ice ages recorded on Gondwanan continents. Trans. Geol. Soc. South Africa 86, 237–262.

Darwin, G.H., 1880. On the secular changes in the elements of the orbit of a satellite revolving about a tidally distorted planet. Phil. Trans. Roy. Soc. London 171 (2), 713–891.

Davies, H.S., Duarte, J.C., Green, M., 2023. Hadean and Archean (4600–2500 Ma). In: Green, M., Duarte, J.C., (Eds.), A Journey Through Tides, Elsevier, 133-141. https://doi.org/10.1016/B978-0-323-90851-1.00020-0.

de Kock, M.O., Luskin, C.R., Djeutchou, C., Wabo, H., 2021. The Precambrian drift history and paleogeography of the Kalahari Craton. In: Pesonen, L.J., Salminen, J., Elming, S-A., Evans, D.A.D., Veikkolainen, T., Ancient Supercontinents and the Paleogeography of Earth, Elsevier, 377-422. https://doi.org/10.1016/B978-0-12-818533-9.00019-9.

de Wit, M.J., 1998. On Archean granites, greenstones, cratons and tectonics: does the evidence demand a verdict? Precambrian Res. 91, 181–226.

Dhuime, B., Hawkesworth, C.J., Delavault, H., Cawood, P.A., 2018. Rates of generation and destruction of the continental crust: implications for continental growthPhil. Trans. R. Soc. A.37620170403 20170403.

Donaldson, J.A., Eriksson, P.G., Altermann, W., 2002. Actualistic versus non-actualistic conditions in the Precambrian: a reappraisal of an enduring discussion. In: Altermann, W., Corcoran, P.L., (Eds.), Precambrian Sedimentary Environments: A Modern Approach to Ancient Depositional Systems, I.A.S. Spec. Pub., 33, 3-13.

Donnelly, T.H., Crick, I.H., 1988. Depositional environment of the middle Proterozoic Velkerri formation in northern Australia: geochemical evidence. Precam. Res. 42, 165–172.

Einsele, G., 2000. Sedimentary Basins: Evolution, Facies and Sediment Budget, 2nd edn. Springer, Berlin.

Eriksson, P.G., Simpson, E.L., Eriksson, K.A., Bumby, A.J., Steyn, G.L., Sarkar, S., 2000. Muddy roll-up structures in siliciclastic interdune beds of the c 1.8 Ga Waterberg Group. South Africa. Palaios 15, 177–183. https://doi.org/10.2307/3515640.

Eriksson, P.G., Martins-Neto, M.A., Nelson, D.R., Aspler, L.B., Chiarenzelli, J.R., Catuneanu, O., 2001. An introduction to Precambrian basins: their characteristics and genesis. Sed. Geol. 141–142, 1–35. https://doi.org/10.1016/S0037-0738(01)00066-5.

Eriksson, P.G., Catuneanu, O., Sarkar, S., Tirsgaard, H., 2005. Patterns of sedimentation in the Precambrian. Sed. Geol. 176, 17–42. https://doi.org/10.1016/j.sedgeo.2005.01.003.

Eriksson, P.G., Banerjee, S., Catuneanu, O., Sarkar, S., Bumby, A.J., Mtimkulu, M.N., 2007. Prime controls on Archaean-Palaeoproterozoic sedimentation: change over time. Gondwana Research 12, 550–559.

Eriksson, P.G., Altermann, W., Nelson, D.R., Mueller, W.U., Catuneanu, O., 2004. Sedimentation through time. In: Eriksson, P.G., Altermann, W., Nelson, D.R., Mueller, W.U., Catuneanu, O., (Eds.), Developments in Precambrian Geology, Elsevier, 12, 593-680. https://doi.org/10.1016/S0166-2635(04)80009-4.

Eriksson, K.A., Simpson, E.L., 1998. Controls on spatial and temporal distribution of Precambrian eolianites. Sed. Geol. 120, 275–294. https://doi.org/10.1016/S0037-0738(98)00036-0.
Eriksson, K.A., Simpson, E., 2011. Precambrian tidal facies. Springer, Netherlands, In Principles of tidal sedimentology Dordrecht, pp. 397–419.
Eugster, H.P., 1980. Geochemistry of evaporitic lacustrine deposits. Ann. Rev. Earth Planet. Sci. 8, 35–63.
Evans, D.A.D., Smirnov, A.V., Gumsley, A.P., 2017. Paleomagnetism and U-Pb geochronology of the Black Range dykes, Pilbara Craton, Western Australia: a Neoarchean crossing of the polar circle. Aust. J. Earth Sci. 64, 225–237.
Eyles, N., Januszczak, N., 2004. 'Zipper-rift': a tectonic model for Neoproterozoic glaciations during the breakup of Rodinia after 750 Ma. Ear. Sci. Rev. 65, 1–73. https://doi.org/10.1016/S0012-8252(03)00080-1.
Fedo, C.M., Myers, J.S., Appel, P.W., 2001. Depositional setting and paleogeographic implications of earth's oldest supracrustal rocks, the > 3.7 Ga Isua Greenstone belt. West Greenland. Sed. Geol. 141, 61–77.
Fedorchuk, N.D., Dornbos, S.Q., Corsetti, F.A., Isbell, J.L., Petryshyn, V.A., Bowles, J.A., Wilmeth, D.T., 2016. Early non-marine life: Evaluating the biogenicity of Mesoproterozoic fluvial-lacustrine stromatolites. Precambr. Res. 275, 105–118. https://doi.org/10.1016/j.precamres.2016.01.015.
Feulner, G., 2012. The faint young Sun problem. Rev. Geophys. 50 https://doi.org/10.1029/2011RG000375.
Finke, N., Simister, R.L., O'Neil, A.H., Nomosatryo, S., Henny, C., MacLean, L.C., Canfield, D.E., Konhauser, K., Lalonde, S.V., Fowle, D.A., Crowe, S.A., 2019. Mesophilic microorganisms build terrestrial mats analogous to Precambrian microbial jungles. Nat Commun 10, 4323. https://doi.org/10.1038/s41467-019-11541-x.
Fralick, P.W., Miall, A.D., 1989. Sedimentology of the Lower Huronian Supergroup (Early Proterozoic), Elliot Lake area, Ontario, Canada. Sed. Geol. 63, 127–153.
François, C., Pubellier, M., Robert, C., Bulois, C., Jamaludin, S.N.J., Oberhänsli, R., Faure, M., St-Onge, M.R., 2022. Temporal and spatial evolution of orogens: A guide for geological mapping. Episodes 45, 265–283.
Friedman, G.M., Sanders, J.E., Kopaska-Merkel, D.C., 1992. Principles of Sedimentary Deposits. Macmillan, New York, p. 717.
Goldblatt, C., Lenton, T., Watson, A., 2006. Bistability of atmospheric oxygen and the Great Oxidation. Nature 443, 683–686. https://doi.org/10.1038/nature05169.
Goodwin, A.M., 1991. Precambrian Geology: The Dynamic Evolution of the Continental Crust. Academic Press, San Diego.
Goosman, E.A., Catling, D.C., Som, S.M., Altermann, W., Buick, R., 2018. Eolianite Grain Size Distributions as a Proxy for Large Changes in Planetary Atmospheric Density. JGR Plan. 123, 2506–2526. https://doi.org/10.1029/2018JE005723.
Harland, W.B., 1981. The Late Archaean (?) Witwatersrand conglomerates, South Africa. In: Hambrey, M.J., Harland, W.B. (Eds.), Earth's Pre-Pleistocene Glacial Record. Cambridge University Press, Cambridge, pp. 185–188.
Harrison, M.T., 2009. The Hadean Crust: Evidence from >4 Ga Zircons. Annu. Rev. Earth Planet. Sci. 37, 479–505. https://doi.org/10.1146/annurev.earth.031208.100151.
Hawkesworth, C.J., Brown, M., 2018. Earth dynamics and the development of plate tectonics. Philos. Trans. R. Soc. Lond. Seri. Math. Phys. Eng, Sci, p. 376.
Hawkesworth, C.J., Cawood, P.A., Dhuime, B., 2018. Tectonics and crustal evolution. GSA Today 26, 4–11. https://doi.org/10.1130/GSATG272A.1.
Hawkesworth, C.J., Cawood, P.A., Dhuime, B., 2020. The Evolution of the Continental Crust and the Onset of Plate Tectonics. Front. Earth Sci. 8 https://doi.org/10.3389/feart.2020.00326.
Hoffman, P.F., Schrag, D.P., 2002. The snowball Earth hypothesis: testing the limits of global change. Terra Nova 14, 129–155.
Hoffman, P.F., 1976. Environmental Diversity of Middle Precambrian Stromatolites. In: Walter, M.R., (Ed.), Developments in Sedimentology, 20, 599-611. https://doi.org/10.1016/S0070-4571(08)71161-0.
Holland, H.D., 2006. The oxygenation of the atmosphere and oceans. Royal Society of London Philosophical Transactions, Ser. B 361, 903915. https://doi.org/10.1098/rstb.2006.1838.
Huang, C., Li, Z.X., 2023. Why supercontinents became shorter lived as the Earth evolved. Sci Bull (beijing) 68, 436–440.
Huang, S.-F., Wang, W., Kerr, A.C., Zhao, J.-H., Xiong, Q., Wang, J., 2021. The Fuchuan Ophiolite in South China: Evidence for Modern-Style Plate Tectonics During Rodinia Breakup. Geochem. Geophys. Geosyst. 22. e2021GC010137.
Hunter, R.E., 1977. Basic types of stratification in small eolian dunes. Sedimentology 24, 361–387.
Hunt, B.G., 1979. The Influence of the Earth's Rotation Rate on the General Circulation of the Atmosphere. J. Atmos. Sci. 36, 1392–1408. https://doi.org/10.1175/1520-0469(1979)036<1392:TIOTER>2.0.CO;2.
Ielpi, A., Ventra, D., Ghinassi, M., 2016. Deeply channelled Precambrian rivers: Remote sensing and outcrop evidence from the 1.2 Ga Stoer Group of NW Scotland. Precam. Res. 281, 291–311.
International Commission on Stratigraphy, 2022. International Stratigraphic Chart, v2022/03. Retrieved from. https://stratigraphy.org/chart.
Iversen, J.D., White, B.R., 1982. Saltation threshold on Earth, Mars and Venus. Sedimentology 29, 111–119.
Kasting, J.F., Howard, M.T., 2006. Atmospheric composition and climate on the early Earth. Philos Trans R Soc Lond B Biol Sci 361, 1733–1741. https://doi.org/10.1098/rstb.2006.1902.
Kavanagh, L., Goldblatt, C., 2015. Using raindrops to constrain past atmospheric density. EPS. 413, 51–58. https://doi.org/10.1016/j.epsl.2014.12.032.
Kingston, D.R., Dishroon, C.P., Williams, P.A., 1983a. Global basin classification. Am. Assoc. Pet. Geol. Bull. 67, 2175–2193.
Kingston, D.R., Dishroon, C.P., Williams, P.A., 1983b. Hydrocarbon plays and global basin classification. Am. Assoc. Pet. Geol. Bull. 67, 2194–2198.
Kirschvink, J.L., 1992. Late Proterozoic Low-Latitude Global Glaciation: The Snowball Earth. In: Schopf, J.W., Klein, C., Des Maris, D. (Eds.), The Proterozoic Biosphere: A Multidisciplinary Study. Cambridge University Press, pp. 51–52.
Kocurek, G., Dott, R.H., 1981. Distinctions and Uses of Stratification Types in the Interpretation of Eolian Sand. J. Sed. Pet. 51, 579–595.
Kocurek, G., Havholm, K.G., 1993. Eolian sequence stratigraphy-a conceptual framework, in: Weimer, P., Posamentier, H., (Eds.), Siliciclastic Sequence Stratigraphy, AAPG Mem. 58, 393-409. https://doi.org/10.1306/M58581C16.
Kok, J.F., Parteli, E.J.R., Michaels, T.I., Karam, D.B., 2012. The physics of wind-blown sand and dust. Rep. Prog. Phys. 75 (10), 106901 https://doi.org/10.1088/0034-4885/75/10/106901.
Komiya, T., Maruyama, S., Masuda, T., Nohda, S., Hayashi, M., Okamoto, K., 1999. Plate tectonics at 3.8–3.7 Ga: field evidence from the Isua accretionary complex, southern West Greenland. J. Geol. 107, 515–554.
Kopp, R.E., Kirschvink, J.L., Hilburn, I.A., Nash, C.Z., 2005. The Paleoproterozoic snowball Earth: a climate disaster triggered by the evolution of oxygenic photosynthesis. PNAS 102, 11131–11136.
Korenaga, J., 2013. Initiation and Evolution of Plate Tectonics on Earth: Theories and Observations. Annu. Rev. Earth Planet. Sci. 41, 117–151. https://doi.org/10.1146/annurev-earth-050212-124208.
Kreslavsly, M.A., Bondarenko, N.V., N.v.,, 2017. Aeolian sand transport and aeolian deposits on Venus: A review. Aeolian Res. 26, 29–46. https://doi.org/10.1016/j.aeolia.2016.06.001.
Kusky, T.M., Li, J.-H., Tucker, R.D., 2001. The Archean Dongwanzi ophiolite complex, North China craton: 2.505-Billion-year-old oceanic crust and mantle. Science 292, 1142–1145.
Kusky, T., Windley, B., Polat, A., 2018. Geological evidence for the operation of plate tectonics throughout the Archean: Records from Archean paleo-plate boundaries. J. Earth Sci. 29, 1291–1303. https://doi.org/10.1007/s12583-018-0999-6.
Laurent, O., Martin, H., Moyen, J.F., Doucelance, R., 2014. The diversity and evolution of late-Archean granitoids: Evidence for the onset of "modern-style" plate tectonics between 3.0 and 2.5Ga. Lithos 205, 208–235. https://doi.org/10.1016/j.lithos.2014.06.012.
Lebeau, L.E., Ielpi, A., 2017. Alluvial channel belts, floodbasins, and aeolian ergs in the Precambrian Meall Dearg Formation (Torridonian of Scotland): Inferring climate regimes from pre-vegetation clastic rock records. Sed. Geol. 357, 53–71. https://doi.org/10.1016/j.sedgeo.2017.06.003.
Leeder, M., 2011. Sedimentology and sedimentary basins: from turbulence to tectonics, 2nd ed. Wiley-Blackwell, Chichester, West Sussex, UK.
Long, D.G.F., 2019. Archean alluvial deposits: A review. Ear. Sci. Rev. 188, 148–175. https://doi.org/10.1016/j.earscirev.2018.11.009.
Marty, B., Zimmermann, L., Pujol, M., Burgess, R., Philippot, P., 2013. Nitrogen isotopic composition and density of the Archean atmosphere. Science 342, 101–104. https://doi.org/10.1126/science.1240971.
McLennan, S.M., Taylor, S.R., 1982. Geochemical constraints on the growth of continental crust. J. Geol. 90, 342–361.
McMahon, S., Matthews, J.J., Brasier, A., Still, J., 2021. Late Ediacaran life on land: desiccated microbial mats and large biofilm streamers. Proc. R. Soc. B Biol. Sci. 288 https://doi.org/10.1098/rspb.2021.1875.
Meert, J.G., Santosh, M., 2017. The Columbia supercontinent revisited. Gondw. Res. 50, 67–83. https://doi.org/10.1016/j.gr.2017.04.011.
Mitchell, A.H.G., Reading, H.G., 1986. Sedimentation and tectonics. In: Reading, H.G. (Ed.), Sedimentary Environments and Facies. Blackwell Scientific, Oxford, pp. 471–519.
Moyen, J.-F., van Hunen, J., 2012. Short-term episodicity of Archaean plate tectonics. Geology 2012 (40), 451–454. https://doi.org/10.1130/G322894.1.
Nance, D.R., Murphy, J.B., Santosh, M., 2014. The supercontinent cycle: A retrospective essay. Gondw. Res. 25, 4–29. https://doi.org/10.1016/j.gr.2012.12.026.
Nelson, B.K., DePaolo, D.J., 1985. Rapid production of continental crust 1.7 to 1.9 b.y. ago: Nd isotopic evidence from basement of the North America mid-continent. Bull. Geol. Soc. Am. 96, 746–754. https://doi.org/10.1130/0016-7606(1985)96<746:RPOCCT>2.0.CO;2.
Nystuen, J.P., 1985. Facies and preservation of glaciogenic sequences from the Varanger ice ages in Scandinavia and other parts of the North Atlantic region. Palaeogeogr., Palaeoclimatol. Palaeoecol. 51, 209–229.
Ohmoto, H., 2004. The Archaean atmosphere, hydrosphere and biosphere. In: Eriksson, P.G., Altermann, W., Nelson, D.R., Mueller, W.U., Catuneanu, O. (Eds.), The Precambrian Earth: Tempos and Events. Elsevier, Amsterdam, pp. 361e388.
Page, N.J., Koski, R., 1973. A Precambrian diamictite below the base of the Stillwater Complex, southwestern Montana. Jour. Research U.S. Geol. Survey 1, 403–414.
Palin, R., Santosh, M., Cao, W., Li, S., Hernández-Uribee, D., Parsons, A., 2020. Secular change and the onset of plate tectonics on Earth. Earth-Sci. Rev. 207, 172. https://doi.org/10.1016/j.earscirev.2020.103172.
Park, L.E., Gierlowski-Kordesch, E.H., 2007. Paleozoic lake faunas: Establishing aquatic life on land. Palaeogeogr. Palaeoclimatol. Palaeoecol. 249, 160–179. https://doi.org/10.1016/j.palaeo.2007.01.008.
Percival, J.A., Skulski, T., Sanborn-Barrie, M., Stott, G.M., Leclair, A.D., Corkery, T., Boily, M., 2012. Geology and tectonic evolution of the Superior Province, Canada. In: Percival, J.A., Cook, F.A., Clowes, R.M., Tectonic Styles in Canada: The Lithoprobe Perspective, Geological Association of Canada, Special Publication 49, 321–78.
Perillo, V.L., Maisano, L., Martinez, A.M., Quijada, I.E., Cuadrado, D.G., 2019. Microbial mat contribution to the formation of an evaporitic environment in a temperate-

latitude ecosystem. J. Hydrol. 575, 105–114. https://doi.org/10.1016/j.jhydrol.2019.05.027.

Pesonen, L.J., Evans, D.A.D., Veikkolainen, T., Salminen, J., Elming, S-A., 2021. Precambrian supercontinents and supercycles—an overview. In: Pesonen, L.J., Salminen, J., Elming, S-A., Evans, D.A.D., Veikkolainen, T., (Eds.), Ancient Supercontinents and the Paleogeography of Earth, 1- 50. https://doi.org/10.1016/B978-0-12-818533-9.00020-5.

Picard, D.M., High, L.R., Jr., 1972. Criteria For Recognizing Lacustrine Rocks. In: Rigby, J.K., Hamblin, W.K., Recognition of Ancient Sedimentary Environments, SEPM Special Publication 16, 108-145. https://doi.org/10.2110/pec.72.02.0108.

Retallack, G.J., 2018. The oldest known paleosol profiles on Earth: 3.46 Ga Panorama Formation Western Australia. Palaeogeogr. Palaeoclimatol. Palaeoecol. 489, 230–248. https://doi.org/10.1016/j.palaeo.2017.10.013.

Rodríguez-López, J.P., Clemmensen, L.B., Lancaster, N., Mountney, N.P., Veiga, G.D., 2014. Archean to Recent aeolian sand systems and their sedimentary record: Current understanding and future prospects. Sedimentology 61, 1487–1534. https://doi.org/10.1111/sed.12123.

Ruz, M.H., Allard, M., 1994. Coastal dune development in cold-climate environments. Phys. Geog. 15, 372–380.

Runyon, K.D., Bridges, N.T., Newman, C.E., 2017. Martian sand sheet characterization and implications for formation: A case study. Aeolian Res. 29, 1–11. https://doi.org/10.1016/j.aeolia.2017.09.001.

Sarkar, S., Banerjee, S., Eriksson, P.G., Catuneanu, O., 2005. Microbial mat control on siliciclastic Precambrian sequence stratigraphic architecture: examples from India. Sed, Geol., p. 176

Schieber, J., 2004. Microbial mats in the siliciclastic rock record: a summary of diagnostic features. In: Eriksson, P.G., Altermann, W., Nelson, D.R., Mueller, W.U., Catuneanu, O. (Eds.), The Precambrian Earth: Tempos and Events. Elsevier, Amsterdam, pp. 663–673.

Schieber, J., Bose, P.K., Eriksson, P.G., Banerjee, S., Sarkar, S., Altermann, W., Catuneanu, O., 2007. Atlas of microbial mat features preserved within the siliciclastic rock record. Atlases in Geoscience, 2, Elsevier, Amsterdam, pp. 311.

Scotese, C.R., 2009. Late Proterozoic plate tectonics and palaeogeography: a tale of two supercontinents, Rodinia and Pannotia. Geol. Soc. Lond. Spec. Publ. 326, 67–83.

Simpson, E.L., Eriksson, K.A., 1993. Thin eolianites interbedded within a fluvial and marine succession: early Proterozoic Whitworth Formation, Mount Isa Inlier. Australia. Sed. Geol. 87, 39–62.

Simpson, E.L., Eriksson, K.A., Muller, W.U., 2012. 3.2 Ga eolian deposits from the Moodies Group, Barberton Greenstone Belt, South Africa: Implications for the origin of first-cycle quartz sandstones. Precambrian Res. 214–215, 185–191. https://doi.org/10.1016/j.precamres.2012.01.019.

Smith, H.T.U., 1966. Wind-formed pebble ripples in Antarctica. Geol. Soc. Am. Spec. Pap. 87, 160.

Smith, C.E., 1998. Modeling high sinuosity meanders in a small flume. Geomorphology 25, 19–30.

Som, S.M., Catling, D.C., Harnmeijer, J.P., Polivka, P.M., Buick, R., 2012. Air density 2.7 billion years ago limited to less than twice modern levels by fossil raindrop imprints. Nature 484 (7394), 359–362. https://doi.org/10.1038/nature10890.

Som, S.M., Buick, R., Hagadorn, J.W., Blake, T.S., Perreault, J.M., Harnmeijer, J.P., Catling, D.C., 2016. Earth's air pressure 2.7 billion years ago constrained to less than half of modern levels: Nat. Geo. 9, 448–451. https://doi.org/10.1038/ngeo2713.

Stern, R.J., Leybourne, M.I., Tsujimori, T., 2016. Kimberlites and the start of plate tectonics. Geology 44, 799–802. https://doi.org/10.1130/G38024.1.

Stewart, A.D., 2002. The later Proterozoic Torridonian rocks of Scotland: their sedimentology, geochemistry, and origin. Geol. Soc. London Mem. 24, 5–21. https://doi.org/10.1144/GSL.MEM.2002.024.01.02.

Strand, K.O., Laajoki, K., 1993. Palaeoproterozoic glaciomarine sedimentation in an extensional tectonic setting: the Honkala Formation. Finland. Precam. Res. 64, 253–271. https://doi.org/10.1016/0301-9268(93)90080-L.

Swanner, E.D., Lambrecht, N., Wittkop, C., Harding, C., Katsev, S., Torgeson, J., Poulton, S.W., 2020. The biogeochemistry of ferruginous lakes and past ferruginous oceans. Earth Sci. Rev. 211, 103430 https://doi.org/10.1016/j.earscirev.2020.103430.

Tirsgaard, H., Øxnevad, I.E.I., 1998. Preservation of pre-vegetational mixed fluvio-aeolian deposits in a humid climatic setting: an example from the Middle Proterozoic Eriksfjord Formation, Southwest Greenland. Sed. Geol. 120, 295–317.

Touma, J., Wisdom, J., 1994. Evolution of the Earth-Moon system. Astron. J. 108, 1943–1961.

Turcotte, D.L., Cisne, J.L., Nordmann, J.C., 1977. On the Evolution of the Lunar Orbit. Icarus 30, 254–266.

Unrug, R., 1984. The mid-Proterozoic Mporokoso Group of northern Zambia: stratigraphy, sedimentation and regional position. Precam. Res. 24, 99–121.

van der Westhuizen, W.A., Grobler, N.J., Loock, J.C., Tordiffe, E.A.W., 1989. Raindrop imprints in the Late Archean-Early Proterozoic Ventersdorp Supergroup, South Africa. Sediment. Geol. 61, 303–309.

Veizer, J., Jansen, S.L., 1979. Basement and sedimentary recycling and continental evolution. J. Geol. 87, 341–370.

Waiser, M.J., Robarts, R.D., 2009. Saline Inland Waters. In: Likens, G.E., (Ed.), Encyclopedia of Inland Waters, Academic Press, pp. 634-644. https://doi.org/10.1016/B978-012370626-3.00028-4.

Watanabe, Y., Martini, J., Ohmoto, H., 2000. Geochemical evidence for terrestrial ecosystems 2.6 billion years ago. Nature 408, 574–578. https://doi.org/10.1038/35046052.

White, B.R., 1982. Venusian saltation. Icarus 46, 226–232.

Wiebols, J.H., 1955. A suggested glacial origin for the Witwatersrand conglomerates. Trans. Geol. Soc. s. Afr. 58, 367–387.

Williams, G.E., 1975. Late Precambrian glacial climate and the Earth's obliquity. Geol. Mag. 112, 441–465.

Williams, G.E., 2000. Geological constraints on the Precambrian history of Earth's rotation and the Moon's orbit. Rev. Geophys. 38, 37–59.

Williams, W.D., Mann, K.H., 2022. 2022. Inland water ecosystem, Encyclopedia Britannica https://www.britannica.com/science/inland-water-ecosystem.

Wilson, I.G., 1973. Ergs. Sed. Geol. 10, 77–106. https://doi.org/10.1016/0037-0738(73)90001-8.

Windley, B.F., 1995. The Evolving Continents, 3rd ed. J. Wiley, Chichester.

Windley, B.F., Kusky, T., Polat, A., 2021. Onset of plate tectonics by the early Archean. Precambr. Res. 352, 980. https://doi.org/10.1016/j.precamres.2020.105980.

Xiong, S.-F., Jiang, S.-Y., Zhao, J.-X., Niu, P.-P., Ma, Y., Bai, X.-Y., 2023. Dating Precambrian sedimentary carbonate strata by in situ U-Pb isotopes of dolomite. Precambr. Res. 107088 https://doi.org/10.1016/j.precamres.2023.107088.

Xie, X., Heller, P.L., 2009. Plate tectonics and basin subsidence history. Bull. Geol. Soc. Am. 121, 55–64. https://doi.org/10.1130/B26398.1.

Young, G.M., 2004. Earth's two great Precambrian glaciations: aftermath of the "Snowball Earth" hypothesis. In: Eriksson, P.G., Altermann, W., Nelson, D.R., Mueller, W.U., Catuneanu, O. (Eds.), The Precambrian Earth: Tempos and Events. Elsevier, Amsterdam, pp. 440–448.

Young, G.M., 2013. Precambrian supercontinents, glaciations, atmospheric oxygenation, metazoan evolution and an impact that may have changed the second half of Earth history. Geosci. Front. 4, 247–261. https://doi.org/10.1016/j.gsf.2012.07.003.

Young, G.M., Gostin, V.A., 1991. Late Proterozoic (Sturtian) succession of the North Flinders Basin, South Australia; an example of temperate glaciation in an active rift setting. In: J.R. Anderson, G.M. Ashley (Eds.), Glacial Marine Sedimentation: Palaeoclimatic Significance, Geological Society of America, 261 (1991), pp. 207–222.

Young, G.M., von Brunn, V., Gold, D.J.C., Minter, W.E.L., 1998. Earth's Oldest Reported Glaciation: Physical and Chemical Evidence from the Archean Mozaan Group (~2.9 Ga) of South Africa. J. Geol. 106, 523–538. https://doi.org/10.1086/516039.

Young, G.M., 2018. Precambrian Glacial Deposits: Their Origin, Tectonic Setting, and Key Role in Earth Evolution. In: Menzies, J., van der Meer, J.J.P., (Eds.), Past Glacial Environments, Elsevier, 17-45. https://doi.org/10.1016/B978-0-08-100524-8.00001-4.

Zegers, T.E., de Wit, M.J., Dann, J., White, S.H., 1998. Vaalbara, Earth's oldest assembled continent? A combined structural, geochronological, and palaeomagnetic test. Terra Nova 10, 250–259.

Zhao, G.C., Cawood, P.A., Wilde, S.A., Sun, M., 2002. Review of global 2.1–1.8 Ga orogens: implications for a pre-Rodinia supercontinent. Earth Sci. Rev. 59, 125–162.

Zhao, G.C., Sun, M., Wilde, S.A., S.z. s.z.,, 2003. Assembly, accretion and breakup of the Paleo-Mesoproterozoic Columbia supercontinent: records in the North China Craton. Gondw. Res. 6, 417–434.