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RESEARCH ARTICLE

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Large igneous provinces track fluctuations in subaerial exposure of continents across the Archean–Proterozoic transition

Janne Liebmann[1] | Christopher J. Spencer[2] | Christopher L. Kirkland[1] | Richard E. Ernst[3,4]

[1]Timescales of Mineral Systems Group, The Institute for Geoscience Research (TIGeR), School of Earth and Planetary Sciences, Curtin University, Perth, Australia

[2]Department of Geological Sciences and Geological Engineering, Queen's University, Kingston, Ontario, Canada

[3]Department of Earth Sciences, Carleton University, Ottawa, Ontario, Canada

[4]Faculty of Geology and Geography, Tomsk State University, Tomsk, Russia

Correspondence
Janne Liebmann, Timescales of Mineral Systems Group, The Institute for Geoscience Research (TIGeR), School of Earth and Planetary Sciences, Curtin University, Perth 6845, Australia.
Email: janne.liebmann@curtin.edu.au

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Abstract

Geological observations and numerical models imply that Archean continents were mostly submarine. In contrast, approximately one third of modern earth's surface area consists of subaerial continental crust. To temporally constrain changes in the subaerial exposure of continents, we evaluate the eruptive environment (submarine vs subaerial) of 3.4–2.0 Ga continental large igneous provinces (LIPs). Our results indicate that up until 2.4 Ga LIPs predominantly erupted onto submerged continents. This period of low freeboard was punctuated by local subaerial eruptions at 2.8–2.7 Ga and 2.5 Ga. From 2.4 Ga–2.2 Ga, extensive subaerial continental volcanism is recorded in six different cratons, supporting widespread subaerial continents at this time. An increase in exposed continental crust significantly impacts atmospheric and oceanic geochemical cycles and the supply of nutrients for marine bioproductivity. Thus, the 2.4–2.2 Ga high-freeboard conditions may have triggered the earliest global glaciation event and the first significant rise of atmospheric oxygen.

1 | INTRODUCTION

Approximately 30% of earth's present surface area consists of subaerial continental crust. On the Archean earth, in contrast, continents may have been mostly submerged (Flament et al., 2008; Johnson & Wing, 2020). Siliciclastic sediments and palaeosols (Buick et al., 1995; Burke et al., 1986; Eriksson et al., 1999; Murakami et al., 2001) indicate that Archean continents (e.g. the Pilbara and Kaapvaal cratons) were at least locally raised above sea level. In the Sighbhum craton, continental emergence above sea level may have begun as early as 3.3.-3.2 Ga (Chowdhury et al., 2021). However, on a global scale, Precambrian sedimentation patterns indicate deposition in predominantly oceanic settings or epeiric seas, and generally low-freeboard conditions (freeboard refers to the average elevation of continents above sea level) until the Neoarchean to early Proterozoic (Campbell & Davies, 2017; Eriksson et al., 2005; Eriksson & Condie, 2014). Limited exposure of Archean continents is supported by geochemical proxies and numerical models (Flament et al., 2013; Johnson & Wing, 2020; Rey & Houseman, 2006). Furthermore, continental flood basalts that erupted in submarine environments are common in the Archean and Palaeoproterozoic, but are rare to absent in the Phanerozoic (Arndt, 1999; Kump & Barley, 2007). A spatially extensive emergence of continents above sea level in the early Palaeoproterozoic era has been inferred from multiple lines of evidence, including a change in the oxygen isotopic ratios of shales (2.43–2.31 Ga; Bindeman et al., 2018) and sediment-derived melts (~2.4 Ga; Liebmann et al., 2021; Spencer et al., 2019), and a 2.5–2.2 Ga increase in $^{87}Sr/^{86}Sr$ ratios of marine carbonate implying increasing continental influence on ocean chemistry through crustal erosive run-off (Chen et al., 2022; Flament et al., 2013; Shields & Veizer, 2002). Furthermore, the volcano-sedimentary record of cratons that make up parts of the present-day continents of Africa, India, Australia, North and South America, and Europe indicate a rapid increase in freeboard at ~2.4 Ga (Eriksson et al., 1999; Eriksson & Condie, 2014). Broadly coincidental, the oldest known widespread, low-latitude glaciation occurred (Rasmussen et al., 2013), and atmospheric O_2 rose to $>10^{-5}$ present atmospheric level (Pavlov & Kasting, 2002), referred to as "Great Oxidation Event" (Holland, 2002). The rise of atmospheric O_2 led to the cessation of mass-independent fractionation of sulphur isotopes (S-MIF) in the atmosphere, evident from the disappearance of large, non-zero $\Delta^{33}S$ values in sedimentary sulphur-bearing minerals after the Great Oxidation Event (Farquhar & Thiemens, 2000). Based on the global large igneous province (LIP) record and the assumption that all post-Archean continental LIPs are emplaced subaerially, Kump and Barley (2007) proposed that subaerial volcanism increased at 2.5 Ga, which leads to a change in the composition of emitted volcanic gases facilitating atmospheric oxygenation (Gaillard et al., 2011). Large igneous provinces represent high volume, short duration (<5 Myr) intraplate magmatic events (Ernst, 2014). They typically consist of flood basalts and a plumbing system of dyke swarms, sills and layered intrusions. Here we present a re-evaluation of the emplacement environment (i.e. subaerial vs. submarine) of 3.4–2.0 Ga continental LIPs. The proportion of subaerial to submarine continental LIPs through time tracks the intervals of enhanced and diminished continental exposure and allows the assessment of potential temporal correlation of freeboard increase with major atmospheric and climatic changes.

Significance Statement

A high sea level and limited subaerial exposure of continents ("water world") in the Archean eon has been inferred from numerical models, geochemical proxies and widespread submarine volcanic eruptions evident in Archean greenstone belts. The emergence of continents above sea level is thought to have occurred at some point in the Eoarchean to Palaeoproterozoic. Previous attempts to constrain the timing of continental emergence largely relied on geochemical signatures, the sedimentary record or numerical models, all of which have some ambiguity (e.g. due to a fragmented record, imprecise age constraints or poorly constrained variables). This study presents an evaluation of the eruptive emplacement environment (subaerial vs. submarine) of continental large igneous provinces that tracks fluctuations in emergent land area. Continental large igneous provinces provide a more direct record of subaerial exposure than geochemical proxies or numerical models and time constraints are in most cases more precise and robust than for the sedimentary record. Our results unravel distinct time intervals of diminished or enhanced subaerial continental large igneous province volcanism and widespread continental emergence between ca. 2.4 and 2.2 Ga. These results imply that the first significant build-up of free oxygen in the atmosphere was coeval with increased subaerial exposure of continents.

2 | DATA SOURCE AND ERUPTIVE ENVIRONMENT CRITERIA

We consider all 3.4–2.0 Ga continental LIPs in the compilation of Ernst et al. (2021) (Figures 1 and 2, Table S1). LIPs that have been classified as oceanic (e.g. oceanic plateaus, ocean basin flood basalts) have been excluded from this evaluation (see Table S1 for a complete list of 3.4–2.0 Ga oceanic and continental LIPs). The most robust criteria for subaerial vs. submarine volcanic emplacement are the eruptive characteristics of extrusive igneous rocks that form a LIP. The presence of pillow lavas and hyaloclastites is strong evidence that indicates a submarine emplacement, whereas amygdaloidal flow tops and columnar jointing are commonly observed in subaerial lava flows (Kerr et al., 2000). Another indicator of the emplacement environment includes sediments intercalated with the extrusive rocks of the LIP. Alluvial, aeolian and lacustrine deposits; weathered horizons; and initial emplacement on eroded land surfaces are characteristics of subaerial environments (Eriksson et al., 1999; Kerr et al., 2000). In contrast, marine clay, carbonates, chert and other marine chemical sediments indicate submarine environments (Eriksson et al., 1999). Intercalated terrigenous sediments deposited in marine environments (e.g. turbidites, tidal sandstones) indicate a partly emerged, partly submerged continent, making any definitive categorization problematic. Hence, intercalated terrigenous continental shelf sediments are not used in this study to discriminate subaerial and submarine LIP emplacement. For many Precambrian LIPs, the intrusive rocks of the magmatic system are the only preserved remnants. Where possible, the eruptive environment of those LIPs (e.g. dyke swarms) is determined based on correlation to coeval extrusive magmatism on the same craton or intracratonic sedimentary successions with reasonable age constraints. A summary of the eruptive environment criteria used in this study is provided in Table 1, and a detailed classification is provided in Table S1.

3 | RESULTS AND DISCUSSION

The eruptive environment could be identified for 40 out of 93 continental LIPs from 3.4 to 2.0 Ga, revealing distinct time intervals of diminished or enhanced subaerial LIP volcanism (Figure 3). The first predominantly subaerial LIPs appear at ca. 2.8–2.7 Ga in the

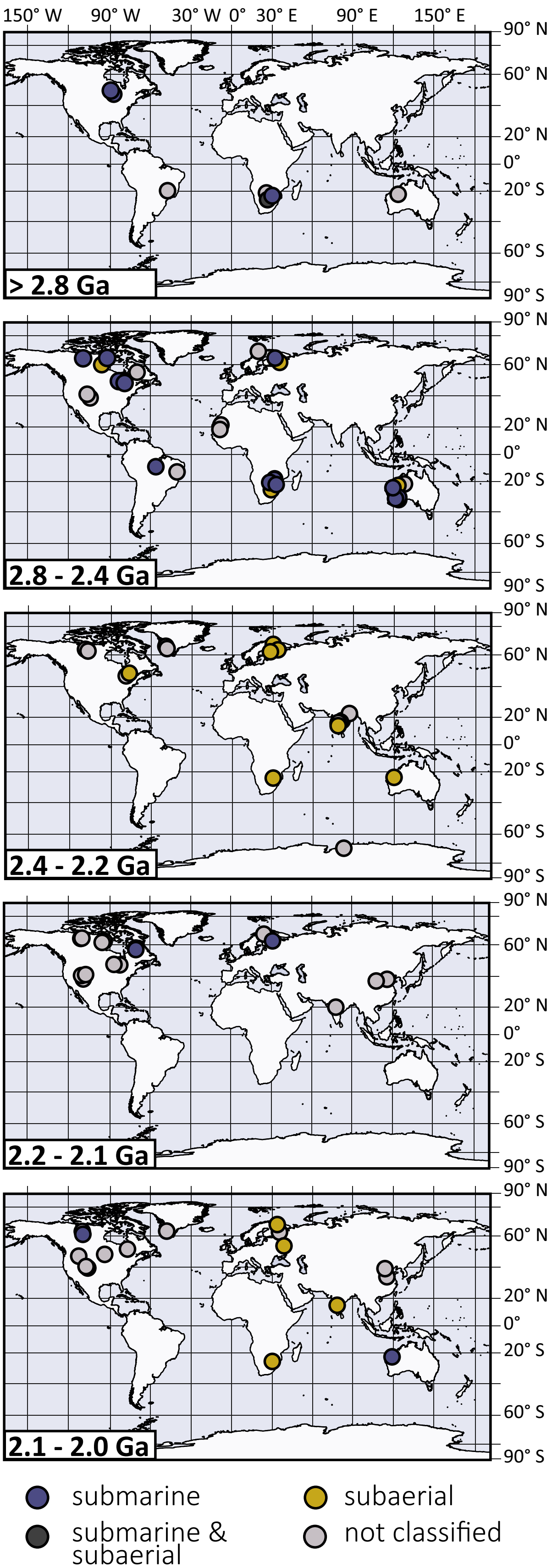

FIGURE 1 Location and eruptive environment of continental LIP events from 3.4 to 2.0 Ga [Colour figure can be viewed at wileyonlinelibrary.com]

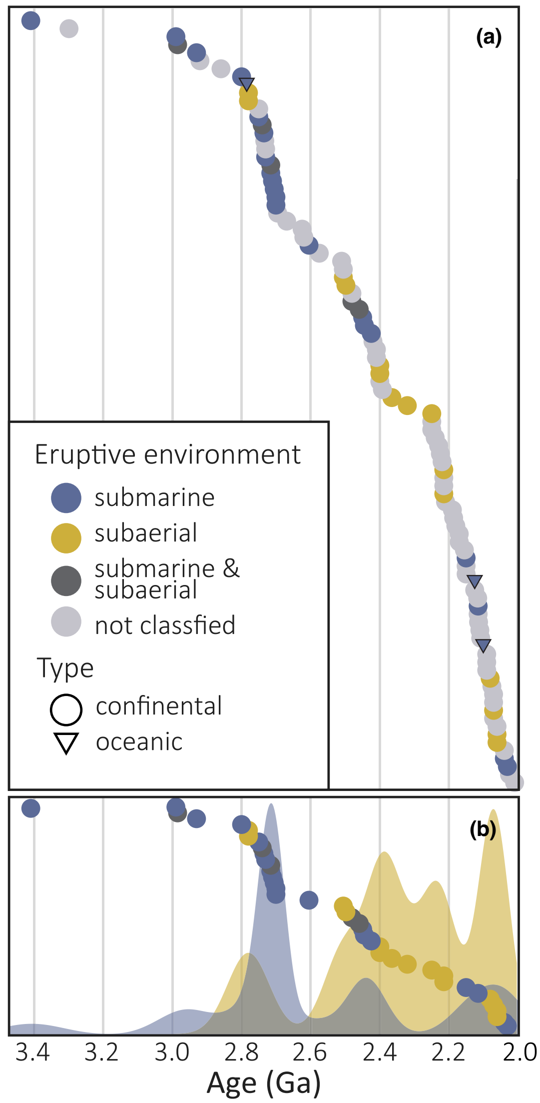

FIGURE 2 Temporal distribution of oceanic and continental LIPs from 3.4 to 2.0 Ga. (a) shows all LIP events, (b) only includes continental LIPs with classified eruptive environment. Curves in (b) are kernel density estimates for submarine (blue curve) and subaerial (yellow curve) continental LIPs. Legend in (a) applies to both parts of the figure [Colour figure can be viewed at wileyonlinelibrary.com]

Kaapvaal and Pilbara cratons, whereas LIPs in other cratons (including the Yilgarn, Superior, Zimbabwe, Slave, Rae and Amazonian cratons) erupted in submarine environments during this time interval. The next occurrence of subaerial LIPs is at ca. 2.5 Ga in the Hearne and Kola-Karelia cratons, followed by multiple submarine and partially submarine LIP emplacements in the Superior, Pilbara, Kola-Karelia and Kaapvaal cratons. The time interval from 2.4 Ga to 2.2 Ga is characterized by widespread subaerial LIP volcanism occurring in six different cratons (including the Superior, Kola-Karelia, Dharwar, Bastar, Kaapvaal and Pilbara cratons), whereas no submarine LIPs were identified. The emplacement environment of only two LIPs could be determined between 2.2 and 2.1 Ga; both of them are

TABLE 1 Criteria for subaerial vs. submarine LIP emplacement

Subaerial criteria	Submarine criteria
Subaerial lava flows (e.g. amygdaloidal flow tops, columnar jointing)	Submarine lava flows (e.g. pillows, hyaloclastites)
Intercalated continental sediments (e.g. alluvial, lacustrine, aeolian deposits)	Intercalated oceanic sediments (e.g. marine clay, carbonates, chert)
Emplacement on weathered horizons or eroded land surfaces	
LIP event coeval with subaerial intracratonic sedimentary succession and/or subaerial extrusive magmatism on the same craton	LIP event coeval with submarine intracratonic sedimentary succession and/or submarine extrusive magmatism on the same craton

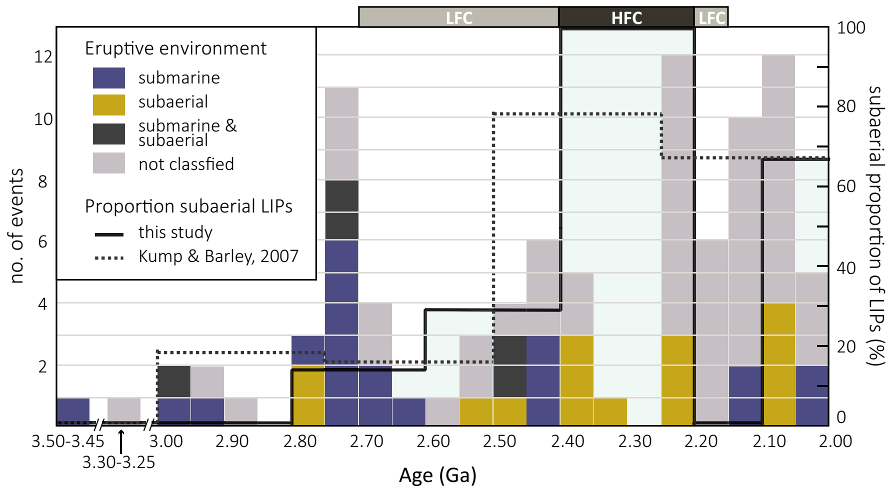

FIGURE 3 Histogram of continental LIP events from 3.4 Ga to 2.0 Ga, colour-coded by eruptive environment. Bin width of the histogram is 50 Ma. Time intervals of global low (LFC) and high-freeboard conditions (HFC), respectively, marked at the top of the figure are from Eriksson et al. (1999) and Eriksson and Condie (2014) based on the supracratonic volcano-sedimentary record. The average proportion of subaerial LIP events for different time intervals is indicated by the solid (this study) and dashed lines (Kump & Barley, 2007); the bin width for the subaerial proportion is equal to the step width of the curves, that is 100–200 Myr for this study and 250 Myr for Kump and Barley (2007). Only LIPs with known eruptive environment are considered to determine the average subaerial proportion. Note that the assessment by Kump and Barley (2007) includes continental and oceanic LIPs, whereas this study only considers continental LIPs [Colour figure can be viewed at wileyonlinelibrary.com]

submarine. Both submarine and subaerial LIPs are recorded for the time interval from 2.1 to 2.0 Ga, including four subaerial events in the Dharwar, Sarmatian, Kola-Karelia and Kaapvaal cratons, and two submarine events in the Slave and Pilbara cratons.

Due to fluctuations in the frequency of LIP events through time, we use proportions rather than absolute numbers as a more meaningful parameter to detect changes in subaerial continental area. Considering only the classified events, the fraction of subaerial LIPs rises from 0% >2.8 Ga to 14% at 2.8–2.6 Ga, to 29% at 2.6–2.4 Ga, to 100% at 2.4–2.2 Ga, then falls to 0% at 2.2–2.1 Ga and rises again to 67% at 2.1–2.0 Ga (Figure 3). The onset of extensive continental subaerial LIP volcanism at ca. 2.4 Ga is in broad agreement with a previous study that suggested an increase in subaerial LIPs from <20% to >70% at 2.5 Ga (Kump & Barley, 2007; Figure 3). Note that the study by Kump and Barley (2007) considers both oceanic and continental LIPs. The fraction of subaerial LIPs in the evaluation presented here is likely underestimated as higher erosional rates and hiatuses in continental sedimentation are a predicted consequence for high freeboard. As a consequence, subaerial LIPs are more likely to remain unidentified. Nonetheless, relative changes in proportions are unlikely to be caused by preservation bias and are interpreted to reflect changes in emergent land area. This is supported by the temporal correlation of changes in freeboard (as determined based on the continental LIP record) with changes in geochemical parameters sensitive to alterations in freeboard, as well as sedimentological evidence (Figures 3 and 4). The time intervals of increased and diminished subaerial LIP volcanism are in good agreement with the time intervals of global low and high freeboard, respectively, as proposed by Eriksson et al. (1999) based on the global supracratonic volcano-sedimentary record (Figure 3). Precambrian sedimentation patterns indicate deposition in predominant oceanic settings or epeiric seas and generally low-freeboard conditions before ~2.42 Ga (Eriksson et al., 2005; Eriksson & Condie, 2014). The onset of the 2.4–2.2 Ga time interval of extensive subaerial LIPs closely matches the 2.35 Ga change in the oxygen isotope composition of sediment melts (Spencer et al., 2019), the 2.43–2.31 Ga shift in the oxygen isotope composition of shales (Bindeman et al., 2018) and overlaps with a 2.5–2.2 Ga change in $^{87}Sr/^{86}Sr$ ratio of marine carbonate rocks (Chen et al., 2022; Flament et al., 2013; Shields & Veizer, 2002), all of which are reasonably linked to an increase in subaerial continental area (Figure 4). In addition, the number of preserved aeolian systems which require subaerial landmasses

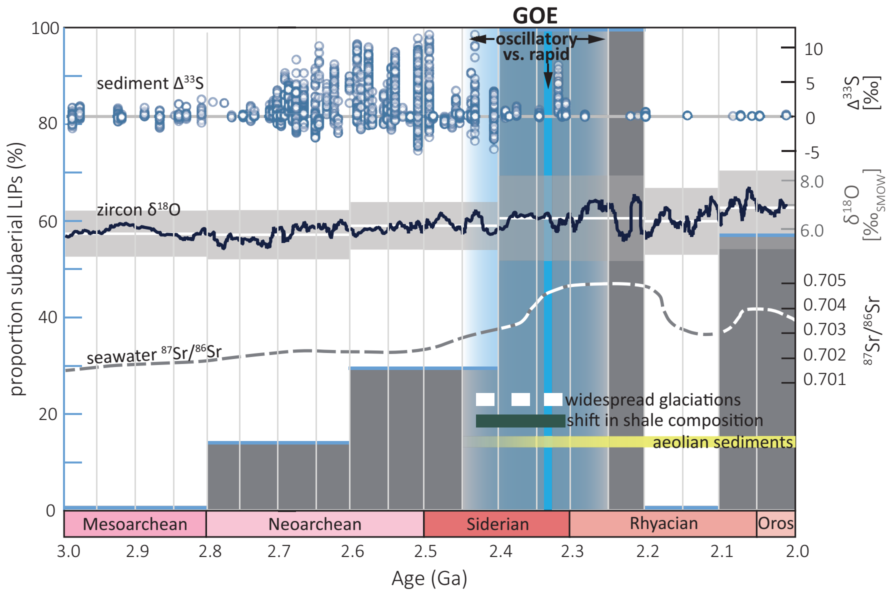

FIGURE 4 Temporal correlation of changes in the eruptive environment of continental LIPs and other geological events at the Archean–Proterozoic transition. Fraction of subaerial LIPs in all classified LIPs is shown as grey boxes (see Figure 3 for details). Timing of atmospheric oxygenation (GOE) is shown after Gumsley et al. (2017) (oscillatory oxygenation) and Luo et al. (2016) (rapid oxygenation). Sedimentary sulphur isotope data are from the compilation of Caruso et al. (2017). Global zircon $\delta^{18}O$ data are from the compilation of Spencer et al. (2022) and shown as moving average (dark line) and binned average with 1σ envelope (white line and grey boxes). The seawater $^{87}Sr/^{86}Sr$ curve is from Chen et al. (2022). Timing of widespread glaciations is from Rasmussen et al. (2013), shift in shale oxygen isotope ratio is from Bindeman et al. (2018) and aeolian systems are from Rodríguez-López et al. (2014); note that the oldest aeolian system at 3.2–3.0 Ga is outside the time interval shown in the diagram [Colour figure can be viewed at wileyonlinelibrary.com]

increases in the Proterozoic (Rodríguez-López et al., 2014). A pervasive erosional event at <2.42 Ga led Eriksson and Condie (2014) to postulate a relatively rapid global-scale drop in sea level potentially related to a ~2.4–2.2 Ga tectono-magmatic slowdown (Condie et al., 2009; Spencer et al., 2018). This proposed lull in mantle activity and concomitant reduced plate velocities (Spencer et al., 2018) and mid-ocean ridge activity (Eriksson & Condie, 2014) may have led to cooling and thickening of the oceanic lithosphere, causing rapid subsidence of the ocean floor and a drop in eustatic sea level (Eriksson & Condie, 2014; Miller et al., 2005). A tectono-magmatic slowdown would likely also affect the efficiencies of lithosphere hydration and dehydration (Rüpke et al., 2004), leading to a decrease in water volume in earth's oceans (Kasting & Holm, 1992). Alternative models to rationalize increased subaerial continental area include thickening and rheologic strengthening of the continental lithosphere enabling formation and sustainability of high mountain belts, decrease in the average density of the continental lithosphere resulting in a higher crustal buoyancy and a decrease in ocean volume related to an increased water storage capacity of the mantle with secular cooling (Campbell & Davies, 2017; Chowdhury et al., 2021; Dong et al., 2021; Flament et al., 2008; Rey & Coltice, 2008; Rey & Houseman, 2006; Vlaar, 2000).

Exceptions to globally low-freeboard conditions before 2.4 Ga are recognized in the LIP record and the sedimentary record (e.g. Eriksson et al., 2005). These local occurrences of high freeboard at 2.8–2.7 Ga and ca. 2.5 Ga have been suggested to reflect mantle plume-related uplift (Eriksson et al., 2002; Eriksson et al., 2005) or the onset of continental emergence (due to changes in crustal thickness and/or density) at different times on different cratons (Campbell & Davies, 2017; Chowdhury et al., 2021). The first recorded occurrence of predominantly subaerial LIPs at ca. 2.8–2.7 Ga is broadly coeval with an increase in magnitude of S-MIF (recorded by sedimentary S-bearing minerals) at 2.7 Ga (Figure 4). This observation supports previously suggested models that link the explosion in maximum magnitude of S-MIF at ca. 2.7 Ga to a change in the composition of volcanic gases (Halevy et al., 2010) associated with increased subaerial volcanism (Gaillard et al., 2011).

Our results are in agreement with low-freeboard conditions from ca. 2.2 to 2.1 Ga as suggested based on the global sedimentary record (Eriksson et al., 1999), even though the number of continental LIPs whose emplacement environment could be determined for this time interval is small (two out of 10). However, strikingly the subsequent increase in subaerial LIP volcanism at 2.1 Ga is accompanied by an increase in seawater $^{87}Sr/^{86}Sr$ ratio and average zircon $\delta^{18}O$ (Figure 4) supporting an increase in freeboard at this time.

4 | CONCLUDING REMARKS

The re-evaluation of the continental LIP record presented here supports extensive subaerial exposure of continents between 2.4 and 2.2 Ga that is temporally correlated with the Palaeoproterozoic rise of O_2 (Holland, 2002) and the oldest known widespread glaciations (Kopp et al., 2005; Rasmussen et al., 2013). Elevated and emerged continental crust may increase the supply of bioessential nutrients (e.g. P and Fe) into oceans, thereby increasing nutrient availability for oxyphotobacteria and thus O_2 production (Campbell & Allen, 2008; Hao et al., 2020). The proportion of submarine to subaerial volcanism would also change (Kump & Barley, 2007), which in turn alters the redox ratio of S in volcanic gases (i.e. towards a higher SO_2/H_2S ratio) facilitating atmospheric oxygenation (Gaillard et al., 2011). The rise of O_2 may have triggered potentially global glaciations (Kopp et al., 2005; Warke et al., 2020). In addition, the enhanced release of SO_2 into the atmosphere as a consequence of subaerial LIP degassing and the subsequent formation of H_2SO_4 aerosols in the stratosphere could have further driven global cooling (Ward, 2009). Furthermore, larger areas of subaerial landmasses increase the albedo of the earth and enhance silicate weathering and associated removal of greenhouse gases from the atmosphere (Barley et al., 2005; Rosing et al., 2010). Our results support a model where Archean continents were locally raised above sea level, which could be responsible for localized accumulations of O_2 in the atmosphere and ocean (O_2-whiffs) before the Great Oxygenation Event (Chowdhury et al., 2021; Lyons et al., 2014; c.f., Slotznick et al., 2022).

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DATA AVAILABILITY STATEMENT

The data that supports the findings of this study are available in the supplementary material of this article

ORCID

Christopher L. Kirkland https://orcid.org/0000-0003-3367-8961

REFERENCES

Arndt, N. (1999). Why was flood volcanism on submerged continental platforms so common in the Precambrian?*Precambrian Research*, *97*, 155–164. https://doi.org/10.1016/S0301-9268(99)00030-3

Barley, M., Bekker, A., & Krepz, B. (2005). Late Archean to Early Paleoproterozoic global tectonics, environmental change and the rise of atmospheric oxygen. *Earth and Planetary Science Letters*, *238*, 156–171. https://doi.org/10.1016/j.epsl.2005.06.062

Bindeman, I. N., Zakharov, D. O., Palandri, J., Greber, N. D., Dauphas, N., Retallack, G. J., Hofmann, A., Lackey, J. S., Bekker, A., & Data, E. (2018). Rapid emergence of subaerial landmasses and onset of a modern hydrologic cycle 2.5 billion years ago. *Nature*, *557*, 545–548. https://doi.org/10.1038/s41586-018-0131-1

Buick, R., Thornett, J. R., McNaughton, N. J., Smith, J. B., Barley, M. E., & Savage, M. (1995). Record of emergent continental crust ~3.5 billion years ago in the Pilbara craton of Australia. *Nature*, *375*, 574–577. https://doi.org/10.1038/375574a0

Burke, K., Kidd, W. S. F., & Kusky, T. M. (1986). Archean Foreland Basin tectonics in the Witwatersrand, South Africa. *Tectonics*, *5*, 439–456. https://doi.org/10.1029/TC005i003p00439

Campbell, I. H., & Allen, C. M. (2008). Formation of supercontinents linked to increases in atmospheric oxygen. *Nature Geoscience*, *1*, 554–558. https://doi.org/10.1038/ngeo259

Campbell, I. H., & Davies, D. R. (2017). Raising the continental crust. *Earth and Planetary Science Letters*, *460*, 112–122. https://doi.org/10.1016/j.epsl.2016.12.011

Caruso, S., Selvaraja, V., Fiorentini, M. and LaFlamme, C., 2017. The global sedimentary sulfur isotope database

Chen, X., Zhou, Y., & Shields, G. A. (2022). Progress towards an improved Precambrian seawater 87Sr/86Sr curve. *Earth-Science Reviews*, *224*, 103869. https://doi.org/10.1016/j.earscirev.2021.103869

Chowdhury, P., Mulder, J. A., Cawood, P. A., Bhattacharjee, S., Roy, S., Wainwright, A. N., Nebel, O., & Mukherjee, S. (2021). Magmatic thickening of crust in non–plate tectonic settings initiated the subaerial rise of Earth's first continents 3.3 to 3.2 billion years ago. *Proceedings of the National Academy of Sciences*, *118*, e2105746118. https://doi.org/10.1073/pnas.2105746118

Condie, K. C., O'Neill, C., & Aster, R. C. (2009). Evidence and implications for a widespread magmatic shutdown for 250 My on Earth. *Earth and Planetary Science Letters*, *282*, 294–298. https://doi.org/10.1016/j.epsl.2009.03.033

Dong, J., Fischer, R. A., Stixrude, L. P., & Lithgow-Bertelloni, C. R. (2021). Constraining the volume of earth's early oceans with a temperature-dependent mantle water storage capacity model. *AGU Advances*, *2*, 1–24. https://doi.org/10.1029/2020AV000323

Eriksson, P., Condie, K., Vader Westhuizen, W., Vader Merwe, R., Bruiyn, H. D., Nelson, D., Altermann, W., Catuneanu, O., Bumby, A., Lindsay, J., and Cunningham, M., 2002. Late Archaean superplume events: a Kaapvaal–Pilbara perspective. *Journal of Geodynamics*, *34*, 207–247https://doi.org/10.1016/S0264-3707(02)00022-4

Eriksson, P. G., Catuneanu, O., Sarkar, S., & Tirsgaard, H. (2005). Patterns of sedimentation in the Precambrian. *Sedimentary Geology*, *176*, 17–42. https://doi.org/10.1016/j.sedgeo.2005.01.003

Eriksson, P. G., & Condie, K. C. (2014). Cratonic sedimentation regimes in the ca. 2450–2000 Ma period: Relationship to a possible widespread magmatic slowdown on Earth?*Gondwana Research*, *25*, 30–47. https://doi.org/10.1016/j.gr.2012.08.005

Eriksson, P. G., Mazumder, R., Sarkar, S., Bose, P. K., Altermann, W., & van derMerwe, R. (1999). The 2.7–2.0 Ga volcano-sedimentary record of Africa, India and Australia: evidence for global and local changes in sea level and continental freeboard. *Precambrian Research*, *97*, 269–302. https://doi.org/10.1016/S0301-9268(99)00035-2

Ernst, R. E. (2014). *Large ignous provinces*. Cambridge University Press.

Ernst, R.E., Bond, D.P.G., Zhang, S., Buchan, K.L., Grasby, S.E., Youbi, N., El Bilali, H., Bekker, A. and Doucet, L.S., 2021. Large igneous province record through time and implications for secular environmental changes and geological time-scale boundaries. 1–26.

Farquhar, J., Bao, H., & Thiemens, M. (2000). Atmospheric influence of Earth's earliest sulfur cycle. *Science*, *289*, 756–759. https://doi.org/10.1126/science.289.5480.756

Flament, N., Coltice, N., & Rey, P. F. (2008). A case for late-Archaean continental emergence from thermal evolution models and hypsometry. *Earth and Planetary Science Letters*, *275*, 326–336. https://doi.org/10.1016/j.epsl.2008.08.029

Flament, N., Coltice, N., & Rey, P. F. (2013). The evolution of the 87Sr/86Sr of marine carbonates does not constrain continental growth. *Precambrian Research*, *229*, 177–188. https://doi.org/10.1016/j.precamres.2011.10.009

Gaillard, F., Scaillet, B., & Arndt, N. T. (2011). Atmospheric oxygenation caused by a change in volcanic degassing pressure. *Nature*, *478*, 229–232. https://doi.org/10.1038/nature10460

Gumsley, A. P., Chamberlain, K. R., Bleeker, W., Söderlund, U., deKock, M. O., Larsson, E. R., & Bekker, A. (2017). Timing and tempo of the great oxidation event. *Proceedings of the National Academy of Sciences*, *114*, 1811–1816. https://doi.org/10.1073/pnas.1608824114

Halevy, I., Johnston, D. T., & Schrag, D. P. (2010). Explaining the Structure of the archean mass-independent sulfur isotope record. *Science*, *329*, 204–207. https://doi.org/10.1126/science.1190298

Hao, J., Knoll, A. H., Huang, F., Hazen, R. M., & Daniel, I. (2020). Cycling phosphorus on the Archean Earth: Part I. Continental weathering and riverine transport of phosphorus. *Geochimica et Cosmochimica Acta*, *273*, 70–84. https://doi.org/10.1016/j.gca.2020.01.027

Holland, H. D. (2002). Volcanic gases, black smokers, and the great oxidation event. *Geochimica et Cosmochimica Acta*, *66*, 3811–3826. https://doi.org/10.1016/S0016-7037(02)00950-X

Johnson, B. W., & Wing, B. A. (2020). Limited Archaean continental emergence reflected in an early Archaean ^{18}O-enriched ocean. *Nature Geoscience*, *13*, 243–248. https://doi.org/10.1038/s41561-020-0538-9

Kasting, J. F., & Holm, N. G. (1992). What determines the volume of the oceans?*Earth and Planetary Science Letters*, *109*, 507–515. https://doi.org/10.1016/0012-821X(92)90110-H

Kerr, A. C., White, R. V., & Saunders, A. D. (2000). LIP reading: Recognizing oceanic plateaux in the geological record. *Journal of Petrology*, *41*, 1041–1056. https://doi.org/10.1093/petrology/41.7.1041

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. *Proceedings of the National Academy of Sciences*, *102*, 11131–11136. https://doi.org/10.1073/pnas.0504878102

Kump, L. R., & Barley, M. E. (2007). Increased subaerial volcanism and the rise of atmospheric oxygen 2.5 billion years ago. *Nature*, *448*, 1033–1036. https://doi.org/10.1038/nature06058

Liebmann, J., Spencer, C. J., Kirkland, C. L., Bucholz, C. E., Xia, X.-P., Martin, L., Kitchen, N., & Shumlyanskyy, L. (2021). Coupling sulfur and oxygen isotope ratios in sediment melts across the archean-proterozoic transition. *Geochimica et Cosmochimica Acta*, *307*, 242–257. https://doi.org/10.1016/j.gca.2021.05.045

Luo, G., Ono, S., Beukes, N. J., Wang, D. T., Xie, S., & Summons, R. E. (2016). Rapid oxygenation of Earth's atmosphere 2.33 billion years ago. *Science Advances*, *2*, 1–9. https://doi.org/10.1126/sciadv.1600134

Lyons, T. W., Reinhard, C. T., & Planavsky, N. J. (2014). The rise of oxygen in Earth's early ocean and atmosphere. *Nature*, *506*, 307–315. https://doi.org/10.1038/nature13068

Miller, K. G., Kominz, M. A., Browning, J. V., Wright, J. D., Mountain, G. S., Katz, M. E., Sugarman, P. J., Cramer, B. S., Christie-Blick, N., & Pekar, S. F. (2005). The phanerozoic record of global sea-level change. *Science*, *310*, 1293–1298. https://doi.org/10.1126/science.1116412

Murakami, T., Utsunomiya, S., Imazu, Y., & Prasad, N. (2001). Direct evidence of late Archean to early Proterozoic anoxic atmosphere from a product of 2.5 Ga old weathering. *Earth and Planetary Science Letters*, *184*, 523–528. https://doi.org/10.1016/S0012-821X(00)00344-7

Pavlov, A. A., & Kasting, J. F. (2002). Mass-Independent Fractionation of Sulfur-Isotopes in Archean Sediments: Strong Evidence for an Anoxic Archean Atmosphere. *Astrobiology*, *2*, 27–41.

Rasmussen, B., Bekker, A., & Fletcher, I. R. (2013). Correlation of Paleoproterozoic glaciations based on U–Pb zircon ages for tuff beds in the Transvaal and Huronian Supergroups. *Earth and Planetary Science Letters*, *382*, 173–180. https://doi.org/10.1016/j.epsl.2013.08.037

Rey, P. F., & Coltice, N. (2008). Neoarchean lithospheric strengthening and the coupling of Earth's geochemical reservoirs. *Geology*, *36*, 635. https://doi.org/10.1130/G25031A.1

Rey, P. F., & Houseman, G. (2006). Lithospheric scale gravitational flow: the impact of body forces on orogenic processes from Archaean to Phanerozoic. In S. J. H. Buiter & G. Schreurs (Eds.), *Analogue and Numerical Modelling of Crustal-Scale Processes* (Vol. *253*, pp. 153–167). Geological Society.

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 (C. Bristow, Ed.). *Sedimentology*, *61*, 1487–1534. https://doi.org/10.1111/sed.12123

Rosing, M. T., Bird, D. K., Sleep, N. H., & Bjerrum, C. J. (2010). No climate paradox under the faint early Sun. *Nature*, *464*, 744–747. https://doi.org/10.1038/nature08955

Rüpke, L. H., Morgan, J. P., Hort, M., & Connolly, J. A. (2004). Serpentine and the subduction zone water cycle. *Earth and Planetary Science Letters*, *223*, 17–34. https://doi.org/10.1016/j.epsl.2004.04.018

Shields, G., & Veizer, J. (2002). Precambrian marine carbonate isotope database: Version 1.1. *Geochemistry Geophysics Geosystems*, *3*, 1–12. https://doi.org/10.1029/2001GC000266

Slotznick, S. P., Johnson, J. E., Rasmussen, B., Raub, T. D., Webb, S. M., Zi, J.-W., Kirschvink, J. L., & Fischer, W. W. (2022). Reexamination of 2.5-Ga "whiff" of oxygen interval points to anoxic ocean before GOE. *Science Advances*, *8*, 1–10. https://doi.org/10.1126/sciadv.abj7190

Spencer, C. J., Cavosie, A. J., Morrell, T. R., Lu, G. M., Liebmann, J., & Roberts, N. M. W. (2022). Disparities in oxygen isotopes of detrital and igneous zircon identify erosional bias in crustal rock record. *Earth and Planetary Science Letters*, *577*, 117248. https://doi.org/10.1016/j.epsl.2021.117248

Spencer, C. J., Murphy, J. B., Kirkland, C. L., Liu, Y., & Mitchell, R. N. (2018). Was the supercontinent cycle activated by a Palaeoproterozoic tectono-magmatic lull?*Nature Geoscience*, *11*, 97–101. https://doi.org/10.1038/s41561-017-0051-y

Spencer, C. J., Partin, C. A., Kirkland, C. L., Raub, T. D., Liebmann, J., & Stern, R. A. (2019). Paleoproterozoic increase in zircon δ18O driven by rapid emergence of continental crust. *Geochimica et Cosmochimica Acta*, *257*, 16–25. https://doi.org/10.1016/j.gca.2019.04.016

Vlaar, N. J. (2000). Continental emergence and growth on a cooling earth. *Tectonophysics*, *322*, 191–202. https://doi.org/10.1016/S0040-1951(00)00063-9

Ward, P. L. (2009). Sulfur dioxide initiates global climate change in four ways. *Thin Solid Films*, *517*, 3188–3203. https://doi.org/10.1016/j.tsf.2009.01.005

Warke, M.R., Di Rocco, T., Zerkle, A.L., Lepland, A., Prave, A.R., Martin, A.P., Ueno, Y., Condon, D.J. and Claire, M.W., 2020. The Great Oxidation Event preceded a Paleoproterozoic "snowball Earth": Proceedings of the National Academy of Sciences, 202003090https://doi.org/10.1073/pnas.2003090117.

SUPPORTING INFORMATION

Additional supporting information may be found in the online version of the article at the publisher's website.

Table S1 Large igneous province database.

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