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 volcanic-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 $^{32}$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.

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 plateau, 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
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
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% 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 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). 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]

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 subaerial intracratonic sedimentary succession and/or subaerial extrusive magmatism on the same craton | LIP event coeval with subaerial intracratonic sedimentary succession and/or subaerial 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 87Sr/86Sr ratio of marine carbonate rocks (Chen et al., 2022; Flamet 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...
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 oxygen-photobacteria and thus O₂ production (Campbell & Allen, 2008; Hao et al., 2020). The proportion of submarine to subaerial volcanicism would also change (Kump & Barley, 2007), which in turn alters the redox ratio of S in volcanic gases (i.e. towards a higher SO₂/H₂S ratio) facilitating atmospheric oxygenation (Gaillard et al., 2011). The rise of O₂ may have triggered potentially global glaciations (Kopp et al., 2005; Warke et al., 2020). In addition, the enhanced release of SO₂ into the atmosphere as a consequence of subaerial LIP degassing and the subsequent formation of H₂SO₄ 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 O₂ in the atmosphere and ocean (O₂-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

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