Migration of continental arcs dictates Earth's long-term climate state

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Abstract

Earth has experienced multiple shifts between icehouse and greenhouse climate states over multimillion-year time scales, yet the dominant geological processes controlling these shifts remain uncertain. Continental arcs have been proposed to play a dual role in the global carbon cycle via volcanic and metamorphic degassing, as well as the chemical weathering of silicate rocks. Here we reconstructed the paleogeographic extent of active and extinct continental arcs to evaluate the global net degassing and weatherability over geological time. Our results show that prolonged glacial intervals are associated with shorter active continental arcs at mid-high latitudes and longer extinct continental arcs at low latitudes. Conversely, short-lived glacial intervals coincide with longer active continental arcs at mid-high latitudes and extinct continental arcs at low latitudes, or a reduction in the length of active continental arcs at mid-high latitudes combined with a moderate length of extinct continental arcs at low latitudes. We also observe that the length of active or extinct continental arcs at low latitudes increases during long-lived greenhouse intervals, potentially preventing a runaway greenhouse effect through increasing global weatherability. Our findings suggest that the importance of the development of continental arcs along latitudinal migration controlling Earth's climate state.

Introduction

The Earth's climate has alternated between icehouse and greenhouse climate states over geological history, which is attributed to variations in the partial pressure of atmospheric CO_2 (pCO_2)[1–3]. Over million-year timescales, atmospheric pCO_2 levels are controlled primarily by inputs from magmatic and metamorphic outgassing, and primarily by outputs from the chemical weathering of silicate rocks[3–5]. Prolonged imbalances between the magnitude of the geological sources and sinks of CO_2 favour the emergence of icehouse intervals, such as the Cryogenian, Late Ordovician, Late Paleozoic, and Mid-Late Cenozoic, or greenhouse intervals, such as the Early Paleozoic and Mesozoic to Early Cenozoic, over the past ~ 720 Myr[6–7]. Proposed driving mechanisms for the periodic onset of icehouse conditions include increased weathering rates through mountain building[8–9], reduced continental arc activity or length[6,10–13], the drift of mafic large igneous provinces (LIPs) through the tropics[14–16], and increased suture length associated with arc-continent collisions within the tropics[7,17]. To date, however, it still remains much debated which periodic processes dominate the climate transitions over geological time scales.

Continental arc magmatism emits more CO_2 than other volcanic systems owing to the interaction of magmas with carbonates stored in the overlying continental plate[10,18,19]. As a result, it has been hypothesized that a global chain of active continental arcs might significantly contribute to increased atmospheric pCO_2 levels, potentially leading to long-term climatic warming, such as during the Cretaceous greenhouse[10,11]. Evidence from detrital zircon records and continental arc reconstructions has suggested covariation between the major climate shifts and variations in continental arc activity (as typically indicated by the length of these chains), which provides support for their role in governing icehouse-greenhouse variability through time[6,10,12,13]. Specifically, periods of increased continental arc activity coincide with greenhouse intervals, and vice versa. However, the changes in continental arc activity are in accordance with the prolonged icehouse and greenhouse intervals, but do not correspond to the short-lived ones (Fig. 1).

Theoretically, enhanced continental arc activity not only increases global inputs of CO_2, contributing to global warming; but it is typically also accompanied by extensive crustal thickening and rapid topographic uplift (i.e., continental arc orogeny), leading to high erosion rates and orogenic precipitation[23–25]. These conditions ultimately augment the global weatherability and drawdown of atmospheric pCO_2 levels during the increased continental arc activity or length, and vice versa. Strong correlations between the continental arc length and strontium isotope ratios in seawater has provided support for its role in dominating global chemical weathering, especially during greenhouse intervals[26]. This observation motivates a reexamination of the correlation between climate shifts and changes in the net outgassing from continental arcs over geological timescales. More intriguingly, continued erosion from remnant topography would cause extinct continental arcs to transition into a net carbon sink after the termination of magmatism, lasting over 50 Myr[23,25]. Global weatherability arising from extinct Cretaceous-Paleogene continental arcs has been invoked to explain a specific cooling episode during the Mid-Late Cenozoic[23]. However, it remains unclear whether the intervals of cool climate are associated with the enhanced global weatherability arising from extinct continental arcs.

Notably, the tropical rain belt is located below the ascending branch of the Hadley circulation, which has consistently remained within the low latitudes throughout Earth's history[27]. During icehouse and greenhouse intervals, the tropics remain relatively warm and wet with high weathering rates[7,15,28]. Global weatherability is therefore influenced by paleogeographic changes in the tropics over geological time. Here we utilized a global database of continental arc length[13] coupled with paleogeographic reconstructions to evaluate the long-term climate variability linked to the latitudinal migration of both active and extinct continental arcs.

Latitudinal length of active and extinct arcs

The total length of active continental arcs calculated by using a 5 Myr timestep is broadly in agreement with that of ref. 13 (Fig. 2a) (See Methods) (Extended Data Tables 1–3). We identified the four lows in the length of active continental arcs between ± 20°and ± 90° of latitude during the Late Tonian-Early Cryogenian (~ 750 – 680 Ma), Cambrian-Early Ordovician (~ 545 – 460 Ma), Devonian-Carboniferous (~ 415 – 300 Ma), Late Cenozoic (~ 35 – 0 Ma), which are in accordance with the prolonged icehouse intervals (Fig. 2b and Extended Data Fig. 1).

By contrast, the three peaks are distributed in the Late Cryogenian-Late Ediacaran (~ 660 – 550 Ma), Late Ordovician-Silurian (~ 455 – 420 Ma), and Early Permian-Early Paleogene (~ 295 – 40 Ma), where the mean length is up to about 2 to 3 times that of the present-day length. When the latitude is between ± 30°and ± 90° of latitude, the peaks in the length of active continental arcs shift to two distinct periods: the

Late Cryogenian-Late Ediacaran (~ 655 – 550 Ma) and the Early Triassic-Late Cretaceous (~ 250 – 70 Ma) (Fig. 2b), which align with the long-lived greenhouse intervals. Notably, during the Early Cambrian-Early Ordovician (~ 545 – 460 Ma) greenhouse interval, tropical regions (i.e., ± 20°latitudes of the equator) contain a remarkably high proportion of active continental arcs, peaking at ~ 60% of the total global length (Fig. 2b and Extended Data Fig. 2).

After the termination of magmatism, the global length of extinct continental arcs on plate reconstructions with time lags of 10–50 Myr was up to ~ 20,000 km during the Late Cryogenian-Late Jurassic, which is approximately half of the length (~ 39,000 km) during the Early Cretaceous-Paleogene (Extended Data Table 4). However, the peaks in the length of all latitudes are inconsistent with the glacial intervals (Fig. 3a and Extended Data Fig. 3). The major peaks in the length of low latitudes occur in the Late Cryogenian (~ 655 – 610 Ma), Late Ordovician (~ 475 – 430 Ma), Late Devonian (~ 375 – 360 Ma), Carboniferous-Early Permian (~ 325 – 290 Ma), Late Jurassic (~ 175 – 150 Ma), Early Cretaceous (~ 140 – 95 Ma) and Cenozoic (~ 65 – 0 Ma), which align with the long-lived and short-lived glacial intervals (Figs. 3b, 3c; Extended Data Figs. 4–6; Extended Data Table 4). Interestingly, within 10–20 Myr after the termination of magmatism, the increased length of extinct continental arcs at low latitudes is observed to align with prolonged glacial intervals such as the Carboniferous-Permian and Mid-Late Cenozoic glaciations, as well as a period of severe cold climate state known as the Marinoan Snowball Earth glaciation (Extended Data Figs. 5–6 and Fig. 4).

In combination with the changes in active continental arc length at mid-high latitudes, it could be suggested that during long-lived glacial intervals like the Carboniferous-Permian and Mid-Late Cenozoic, the length of active continental arcs in mid-high latitudes decreased, while the length of extinct continental arcs in low latitudes increased. In contrast, two possible scenarios occur during short-lived glacial intervals: an increase in the length of active continental arcs at mid-high latitudes and extinct continental arcs at low latitudes, as observed during the Marinoan, Late Ordovician, and Late Jurassic-Early Cretaceous glaciations. Alternatively, a reduction in the length of active continental arcs at mid-high latitudes, combined with a moderate length of extinct continental arcs at low latitudes, occurred during the Late Devonian glaciation (Figs. 2–4). This observation supports the conclusion that Earth's climate state is strongly controlled by variations in the length of active and extinct continental arcs along the latitudinal migration over geological time scales.

Fundamental importance for arc outgassing

Grounded ice sheets are believed to have extended to sea level near the equator during the Sturtian Snowball Earth glaciation (~ 716 – 660 Ma)[21,22], which would have required anomalously low levels of atmospheric CO_2 (refs. 29–31). A previous model has suggested that the break-up of the Rodinia supercontinent led to a marked increase in runoff within the tropics before the Sturtian glaciation[32]. Our study shows that the length of active continental arcs was a minimal (mean value = ~ 8,400 km) prior to the Sturtian glaciation (Fig. 1 and Extended Data Table 2), with more than 60% of the arcs situated within the tropical zone that would promote CO_2 consumption by increasing chemical weathering rates.

Therefore, we infer that a drop in the net outgassing from active continental arcs might give rise to a cool background climate state, which played a crucial role in initiating the Sturtian glaciation.

Once the Earth enters a Snowball Earth state, it causes normal weathering processes like precipitation, erosion, and runoff, and thus continental weathering, to shut down[4,22]. Without the chemical weathering feedback, the net outgassing from active continental arcs in low latitudes would be of equal significance to those in mid-high latitudes. The length significantly increased to about 16,000 km (mean value) at the termination of the Marinoan glaciation. This increase was largely due to the increase of the Pan-African arc and the emergence of the peri-Gondwana arcs associated with the assembly of the Gondwana supercontinent (Fig. 1), making it comparable to the present-day length (~ 14,000 km). The deglaciation of Snowball Earth requires an extremely high atmospheric pCO_2 level (0.12–0.2 bar, ~ 400–660 PAL, present atmospheric level), which would have accumulated over tens of millions of years[33,34]. Geochemical evidence has been shown to confirm abnormally high levels of pCO_2 following the Marinoan glaciation[35,36]. At the present-day rate of global volcanic outgassing, it would take only 20 Myrs to reach an extremely high atmospheric pCO_2 level (1.0 bar) in the absence of a chemical weathering feedback[4]. We therefore propose that a crucial factor in the deglaciation of Snowball Earth events is an increased net outgassing flux from active continental arcs.

Similarly, we find a notable expansion in the length of active continental arcs at the termination of the Carboniferous-Permian glacial interval, specifically within ± 20°latitudes of the equator (Figs. 1 and 2), due to the increased length of Circum-Pacific arcs associated with the assembly and dispersal of the Pangaean supercontinent. This supports the hypothesis that the increased length of active continental arcs could tip the balance toward a greenhouse climate state[10]. Moreover, our results show that the long-lived glacial intervals during the Paleozoic, i.e., Carboniferous-Permian and Mid-Late Cenozoic glaciations, coincide with periods of active continental arc lows at mid-high latitudes (Figs. 2 and 4). These findings indicate that a reduction in the net outgassing from active continental arcs might engender a low background atmospheric pCO_2, favoring the occurrence of long-lived glacial intervals. Collectively, our study provides strong evidence that fluctuations in net outgassing from active continental arcs played an important role in the transitions between prolonged icehouse and greenhouse climate states.

Global cooling linked to extinct arcs

Although a reduction in the net outgassing from active continental arcs would generate low background atmospheric pCO_2, it would likely be insufficient to initiate a transition of the global climate towards a glacial state (Figs. 1 and 2). The drift of the LIPs into the tropics would enhance weathering of (ultra-) mafic lithologies and CO_2 drawdown, which has been proposed as a major driver for global cooling that initiated the glacial intervals, as illustrated in the cases of Franklin, Deccan and Ethiopian LIPs[14–16]. However, the efficiency of chemical weathering is thought to be dependent on the generation of topography[37]. Numerical simulation and geological evidence for surface subsidence or no to insignificant uplift has been confirmed in many LIPs, such as the Siberian, Wrangellia and Columbia River, and Emeishan LIPs[38–43]. Moreover, there is no significant relationship between the total LIP area, including those in the tropics, and silicate weathering[26] nor the extent of continental ice sheets throughout the Phanerozoic. Rather, the highest tropical LIP areas occur during non-glacial climate states[37]. These results suggest that the chemical weathering associated with the LIPs is not the primary driver of the glacial climate state.

We note a coincidence between global glacial intervals and periods of increased extinct continental arc length in the tropics since the Late Cryogenian. Intriguingly, the changes in their length are strongly correlated with that of active sutures associated with arc-continent collisions during the Phanerozoic glacial intervals[7] (Fig. 4). Previous model suggests that the accelerated weathering of tectonically exhumed oceanic crust in arc-continent collisions has the potential to drive substantial consumption of CO_2 within the tropical zone[17]. The observed strong correlation between the extent of continental ice sheets and tropical suture length throughout the Phanerozoic supports the hypothesis that multiple shifts in climate states are primarily controlled by global weatherability associated with obducted oceanic fragments in the tropics[7]. However, no known ophiolite-bearing sutures occur within the interglacial greenhouse interval between the two Cryogenian glaciations[44]. This finding reinforces the possibility that, even without the weathering of obducted oceanic fragments or LIPs (Fig. 4), the tropical weathering of extinct continental arcs could facilitate CO_2 removal and promote global cooling that pushed Earth into a glacial state.

More intriguingly, there is evidence of a significant drop in global average temperature from the Early Triassic to the Early Cretaceous during the Mesozoic greenhouse interval[45], with estimates suggesting a temperature decline of up to ~ 14°C (Fig. 4). Such a significant decrease in global average temperature is comparable to those observed during the glacial intervals such as the Late Ordovician (~ 16°C), Carboniferous-Permian (~ 13°C), and Late Cenozoic (~ 11°C) (Fig. 4). The LIP emplacement events were more prevalent in the Mesozoic, particularly in the Cretaceous[46] (Fig. 4), perhaps triggering hothouse pulses on the warm climate baseline[13,45,47]. Nonetheless, some workers propose a significant role for weathering of the CAMP (Central Atlantic Magmatic Province) LIP within the tropics in atmospheric CO_2 drawdown during the Mesozoic greenhouse interval[48]. However, the CAMP was emplaced at low relief and subsequently buried during the rifting of the Atlantic[37,49], which could significantly limit its impact on global weatherability.

We observe a coincidence between the global average temperature and the length of extinct continental arcs during the Mesozoic greenhouse interval (Fig. 4). The glacial intervals during the Late Jurassic-Early Cretaceous align with the peaks observed in the tropical length of extinct continental arcs (Figs. 3 and 4, Extended Data Figs. 4–6). More importantly, these extinct continental arcs are primarily derived from the development of the Mesozoic Cordilleran, Indochina-Sumatra, and West Pacific arcs[13], with no known arc-continent collisions[7] (Fig. 4). Taken together, we conclude that the global glaciation events may be strongly controlled by changes in global weatherability associated with extinct continental arcs in the tropics since the Late Cryogenian.

Maintaining a habitable climate state

After the two Cryogenian glaciations, the Earth's climate has experienced multiple pronounced cold-warm fluctuations, yet none of them have led to a severe cold climate state like the episodes of Snowball Earth. Specifically, unlike these events where ice covered the entire Earth[21,22], the continental ice sheets are limited to the mid-high latitudes during the Phanerozoic[27,50] (Fig. 4). The elevated rates of volcanic outgassing, which changes with the length of active subduction zones and continental arcs, gave rise to a warm background climate and prevents the return of Snowball Earth events during the Phanerozoic[51].

When atmospheric pCO_2 levels are high and temperatures elevated, these conditions lead to enhanced weathering of silicate rocks, providing negative feedback on atmospheric CO_2 that prevents the occurrence of a runaway greenhouse condition and is critical to maintaining a habitable climate state[4,5,52]. Our study reveals the length of active and extinct continental arcs experiences a substantial increase in the tropics during the Cambrian and Mesozoic greenhouse intervals, respectively (Figs. 2 and 3, Extended Data Figs. 2–6). This scenario provides robust support for the hypothesis that continental arcs exert a dominant control on global weathering fluxes during greenhouse intervals, which might effectively offset the massive outgassing of CO_2 and maintain the stability of Earth's climate[26]. To summarize, the increased length of continental arcs potentially serves as a crucial barrier in preventing the occurrence of Snowball Earth or a runaway greenhouse climate. We propose that this thermostat helps maintain a habitable climate state in the aftermath of Cryogenian Snowball Earth events.

Declarations

Online content

Any methods, additional references, Nature Portfolio reporting summaries, source data, extended data, supplementary information, acknowledgements, peer review information; details of author contributions and competing interests; and statements of data and code availability are available at XXX.

Data availability

All data necessary to reproduce the results of this work are given in the Extended Data and Source Data. Source data are provided with this paper.

Code availability

More details on the computational methods and tools used for this study are available from the corresponding author upon reasonable request.

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Author contributions

J.Z. and Z.C.Z. developed the project. J.Z. conducted paleogeographic extent of continental arcs and Fourier transform analysis. All authors discussed interpretations of results and their implications. J.Z. wrote the initial manuscript draft, which all authors discussed and edited together.

Competing interests

The authors declare no competing interests.

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Methods

Computing the latitudinal length of active arcs

Our outlines of active continental arcs over the past ~750 Myr were taken from shapefiles (ArcGIS format) compiled by ref. 13, whose paleomaps with fixed time points were reconstructed by using the global plate tectonic model of the PALEOMAP Project[53] implemented in the GPlates software (version 2.3) (https://www.gplates.org/)[54].

Continental arc compilation of ref. 13 is based on the spatial extent of felsic-intermediate plutonic rocks (granitoids) associated with continental arc magmatism that are extracted from the geologic maps (1:5,000,000 to 1:10,000,000) of Eurasia, North and South America, Africa, Australia, and Antarctica. For the Phanerozoic continental arcs, the minimum length is based on the mapped extent of continental arc-related granitoids, whereas the maximum length is based on geological interpretations of the original spatial extent of continental arcs. In most cases, the minimum and maximum lengths of continental arcs are equal during the Phanerozoic period. For the pre-Cambrian arcs, the maximum length is based on geological interpretations from the literature due to the low age resolutions of granitoids on the geological maps, and the minimum length is assigned to a half value of the maximum length (Fig. 1, Extended Data Table 2). Although the total length is calculated by accumulation of each continental arc within the same time frame in an Excel file (Extended Data Table 1)[13], this compilation cannot produce latitudinal extent data of those at any timesteps over geological time.

In this study, we adopted the maximum lengths of continental arcs within the shapefile complied by ref. 13 which were reconstructed from 750 Ma to the present along with the tectonic units by using the global plate tectonic model[53]. We converted shapefiles of continental arc outlines (ArcGIS format) to GPML files (GPlates format), and assigned age attributes (i.e., starting and ending time) for each continental arc in the GPlates software. In the calculation, we employed the *py*GPlates (https://www.gplates.org/docs/pygplates/) (version 0.36) function library and custom Python scripts[55] documented within a Jupyter notebook to produce latitudinal extent data of continental arc length at a 5 Ma timestep for analysis and development of the associated visualizations. The length of active continental arcs was calculated by splitting them into eighteen bands according to latitude (that is, 10 degrees per band).

Discrete Fourier transform analysis

We employed the 'Fast Fourier transform' (FFT) function in MATLAB (2021a) to compute the discrete Fourier transform of the total length of active continental arcs over time. The calculation is performed as follows:

$$Y(k) = \sum_{j=1}^{n} X(j)\, W_n^{(j-1)(k-1)}$$

where $W_n = e^{(-2\pi i)/n}$ is one of n roots of unity. n denotes the number of samples collected from the input data and j and k denote indices of the input matrix, the DFT matrix (Vandermonde matrix) used in the operation, and the output matrix (see MATLAB documentation). Normalization can effectively eliminate impact of the absolute magnitude of the function, ensuring that the data relating to active continental arcs were scaled to range between 0 and 1 before Fourier transform analysis. In our study, the FFT analysis for global length of active continental arcs, which includes maximum and average length calculated by ref. 13 and the length of this reconstruction, yielded consistent outcomes.

Computing the latitudinal length of extinct arcs

Some attempts have been made to quantify the nature of continental arc activity by using extensive datasets of igneous and detrital zircon U-Pb dates. These observations suggest that continental arc activity is not continuous but episodic, with voluminous magmatic flare-ups over tens of millions of years[56-61], i.e., ~30 Ma to ~80 Ma. This scenario is consistent with the observed major periodicities of magmatic flare-ups, evident through statistical analysis of each active continental arc (Extended Data Table 1 and Extended Data Fig. 7a), as well as the Fast Fourier transform analysis on the total length of active continental arcs over time (three major periodicities of 50 Myr, 68 Myr, and 83 Myr (Extended Data Fig. 7b).

We compared the changes in length, exposed bedrock U-Pb zircon ages with displaced detrital zircon U-Pb ages, and calculated magma addition rates in the Cordilleran continental arcs of North America. This comparison shows that the magmatic flare-ups and lulls closely match the inferred changes in the length of active continental arcs (Extended Data Fig. 8), giving confidence in these measures.

For continuously active continental arcs with varying lengths over a long duration, including Altia (480-300 Ma), Antarctic Peninsula (200-50 Ma), Indochina-Sumatra (300-23 Ma), Jiangda-Hoh Xil Shan (240-140 Ma), Kazakhstan (420-300 Ma), Lachlan (450-380 Ma), North American Cordilleran (250-23 Ma), New England (300-230 Ma), South American Cordilleran (250-23 Ma), and West Pacific (270-23 Ma) continental arcs (Extended Data Table 1), we chose the moment of each length change as the initial time for their extinct continental arcs. Although the East African (900-650 Ma) and Brasiliano (800-660 Ma) continental arcs are long-lived features, we have a limited understanding of the changes in their length over time.

In this study, we adopted termination time of active continental arcs as onset time for extinct continental arcs. Excluding the East African and Brasiliano continental arcs, the others have durations ranging from 10 Myr to 110 Myr with a mean = 58 Myr, in accordance with periodicities of voluminous magmatic flare-ups (Extended Data Fig. 7). For each continental arc, like the Peninsular Ranges batholith in southern California within the Mesozoic circum-Pacific continental arc system, it initially served as a net carbon source during the magmatic flare-up, but became a net carbon sink due to the continued erosion from remnant topography after the termination of arc magmatism (lasting over 50 Myr) (ref. 25). This is consistent with the expected timescale over which extinct continental arc systems should contribute to global chemical weathering[26].

Based on these constraints, we constructed mapped extents of extinct continental arcs on paleomaps with time lags of 10-50 Myr in the GPlates software (version 2.3)[54]. In the calculation, we employed the *py*GPlates (https://www.gplates.org/docs/pygplates/) (version 0.36) function library and custom Python scripts[55] documented within a Jupyter notebook to produce latitudinal data of continental arc length at a 5 Myr timestep for analysis and development of the associated visualizations. As before, the length of extinct continental arcs was computed by splitting them into eighteen bands according to latitude (that is, 10 degrees per band).

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Figures

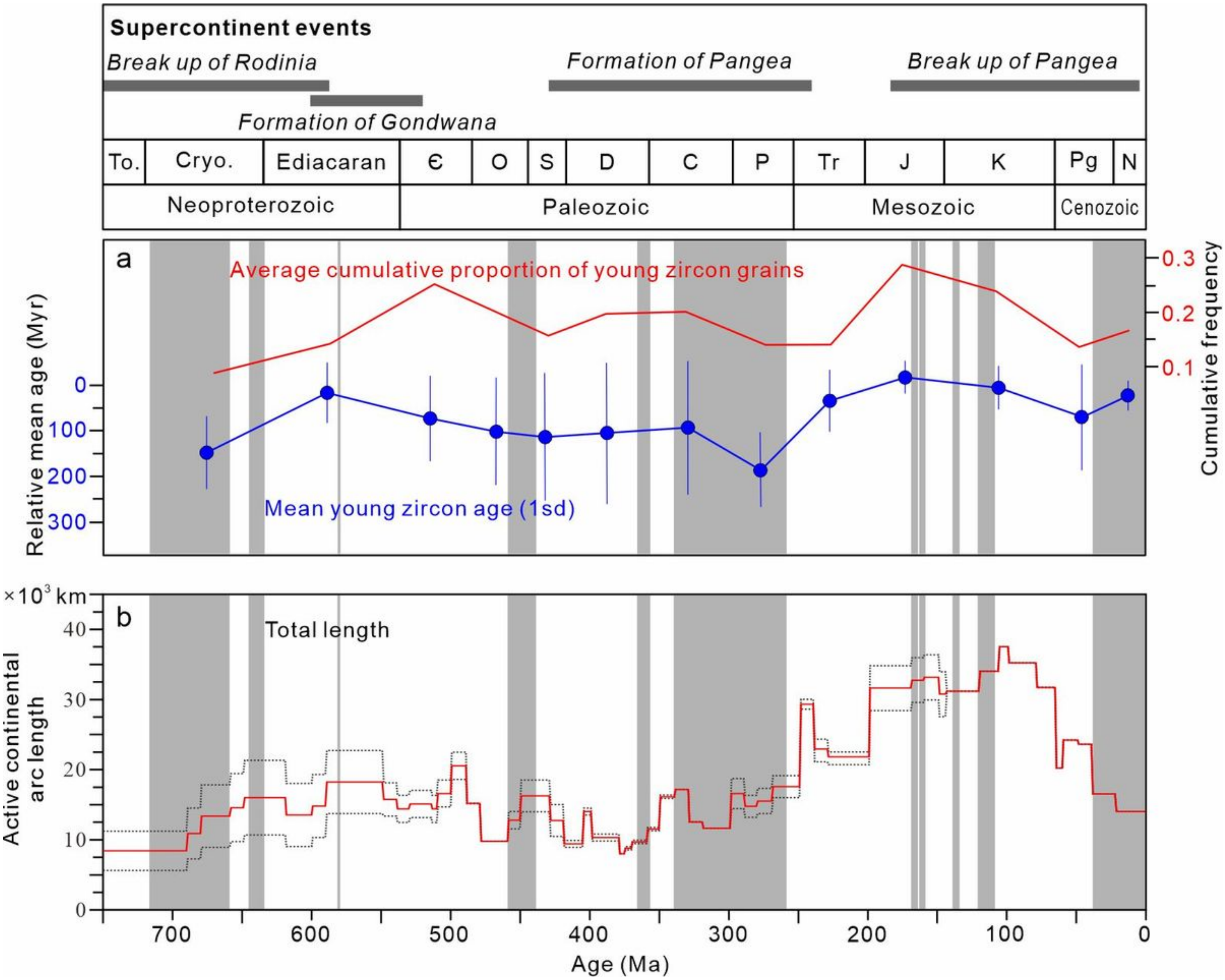

Figure 1

Variations in continental arc activity compared to major glacial intervals over the past ~750 Myr. a, Average cumulative proportion and age of young zircon grains[6]. **b**, Global length of active continental arcs[13]. Red solid line represents average total length, and the gray line represents the maximum and minimum length. Supercontinent events were taken from ref. 13. Grey bands represent major glacial intervals, sourced from refs. 7, 20-22.

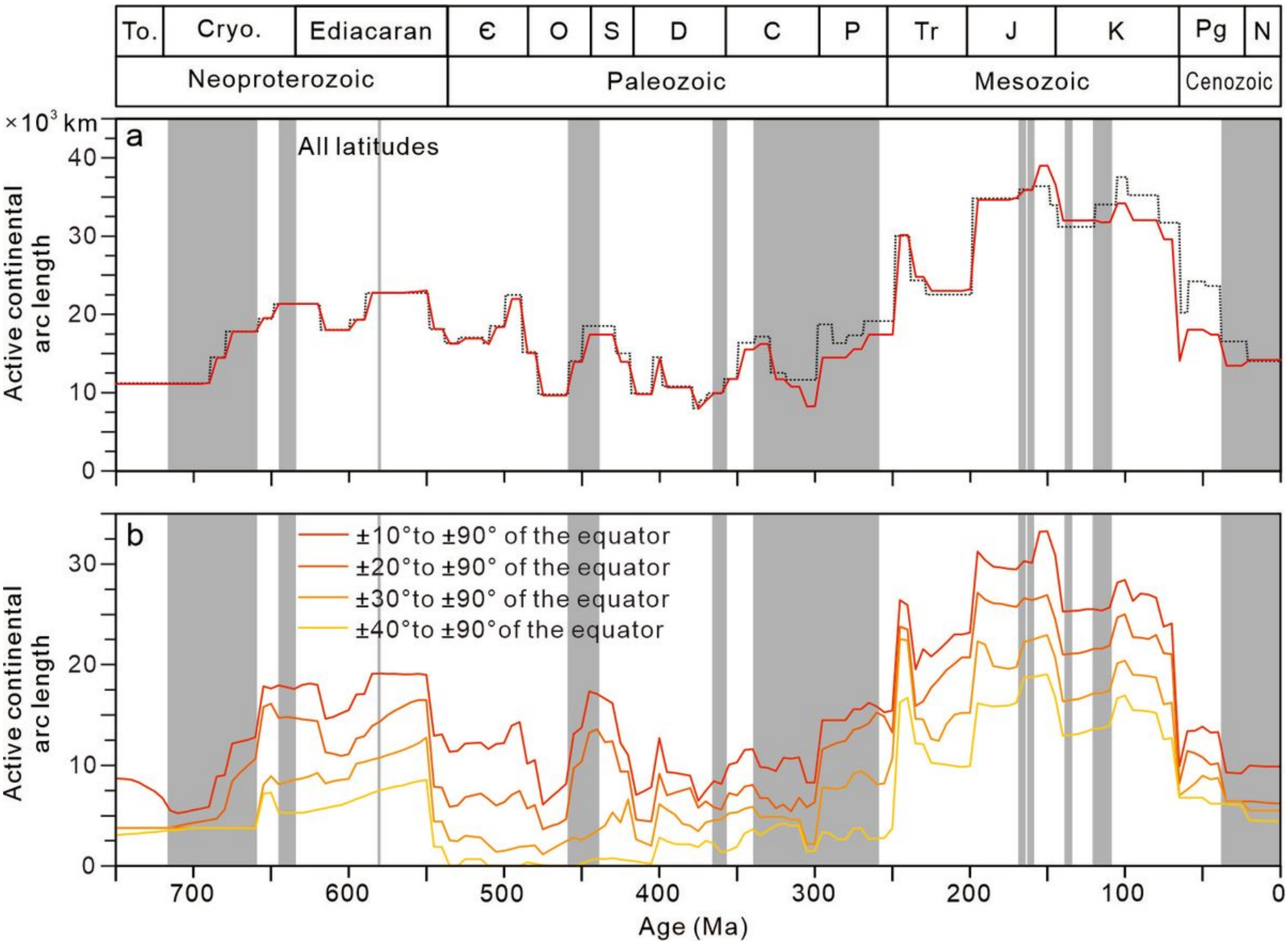

Figure 2

Global length of active continental arcs at mid-high latitudes compared to major glacial intervals over the past ~750 Myr. a, Global length of active continental arcs over the past ~750 Myr. Red solid line represents total length reconstructed by using the global plate tectonic model with a 5 Myr timestep in this study (See Methods), and the gray line represents the total maximum length taken from ref. 13. **b**, Global length of active continental arcs at mid-high latitudes. Grey bands represent major glacial intervals as given in the caption to Fig. 1.

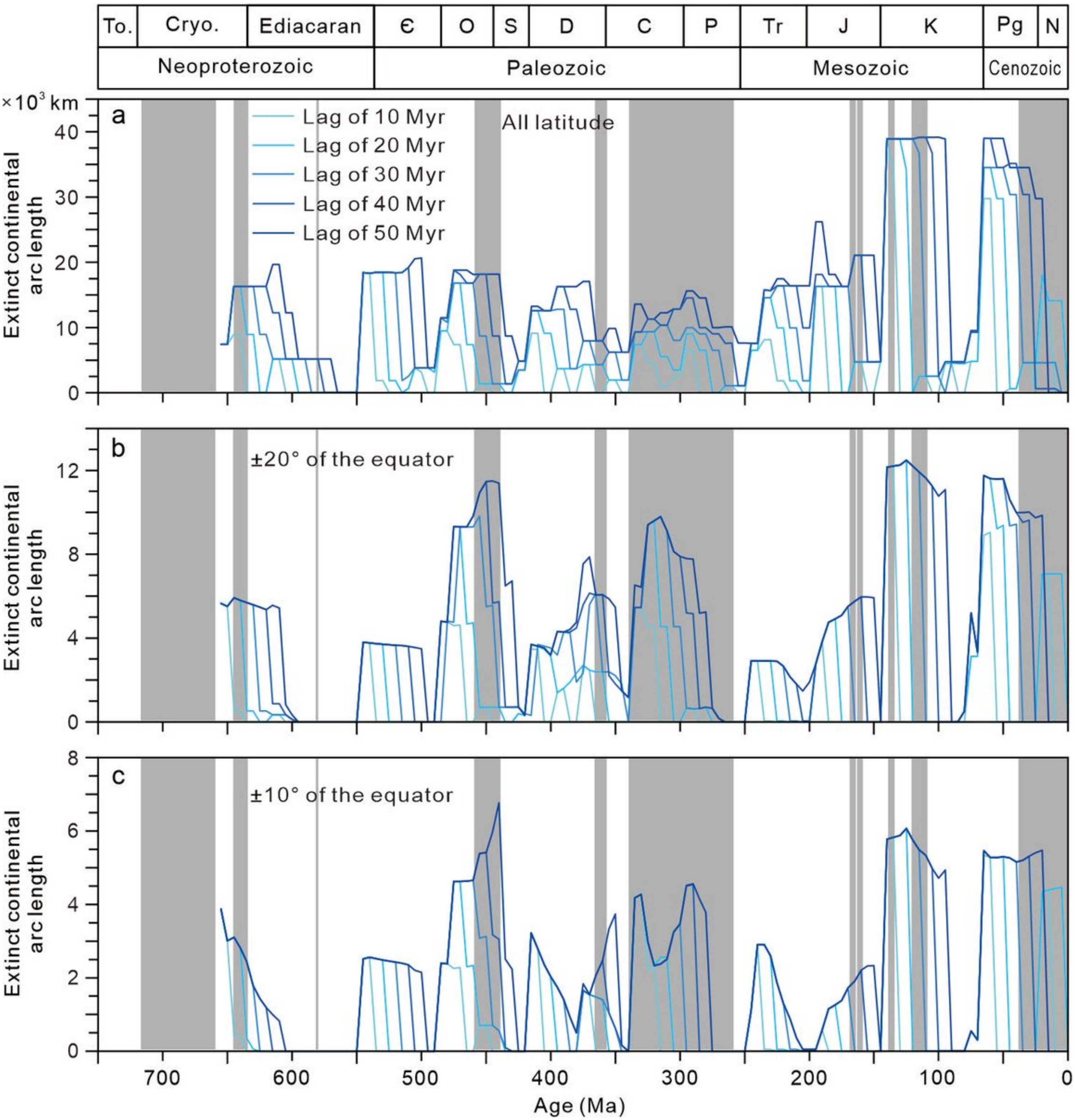

Figure 3

Global length of extinct continental arcs with time lags of 10-50 Myr compared to major glacial intervals over the past ~750 Myr. a, Global length of extinct continental arcs. **b**, Global length of extinct continental arcs within ±20° of the equator. **c**, Global length of extinct continental arcs within ±10° of the equator. Latitudinal length of continental arcs was reconstructed by using the global plate tectonic model with a 5 Myr timestep (see Methods). Grey bands represent major glacial intervals as given in the caption to Fig. 1.

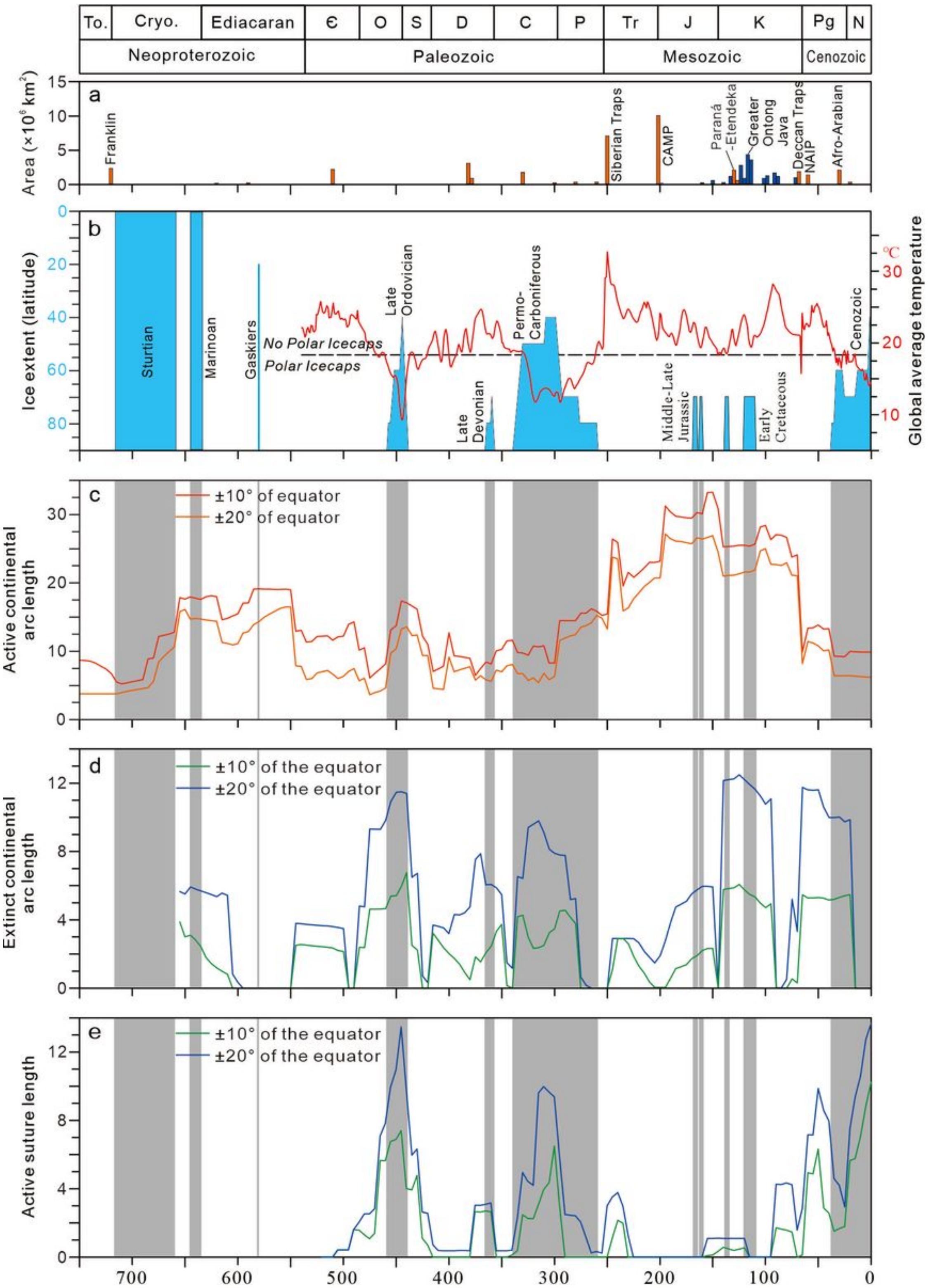

Figure 4

Tectonic and climatic changes over the past ~750 Myr. a, Surface area of mafic large igneous provinces (LIPs, orange and blue bands represent continental and oceanic LIPs respectively)[46]. **b**, Latitudinal extent of continental ice sheets[7,20-22] and global average temperature[45]. **c**, Global length of active continental arcs at mid-high latitudes. **d**, Global length of extinct continental arcs with a time lag of 50 Myr in tropics. **e**, Global length of ophiolite-bearing suture zones in tropics[7].

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- ExtendedDataTables.xlsx
- GPlatesGPMLfiles.zip
- Supplementaryinformationfiles.docx