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Prolonged super-orogens during Gondwana assembly contributed to the formation of a habitable Earth: Insights from big data

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ABSTRACT

Since the initiation of plate tectonics on Earth, the evolution of tectonic regime and supercontinent cycles (Nuna, Rodinia and Pangea) have been the first order factors that contributed to Earth surficial environmental changes and thus development of Earth habitability. In particular, the Neoproterozoic to Cambrian eras recorded dramatic evolution in solid earth and surficial systems, including the breakup of the Rodinia supercontinent and the assembly of the Gondwana (680–430 Ma) landmasses, the Neoproterozoic Oxidation Event (NOE) and Cambrian life diversification. However, the key tectonic factors that were responsible for the evolution of Earth surficial systems during this period remain highly debated and are largely confined to conceptual models. The authors reconstructed the temporal trends of continental orogenic belts, using detrital zircon europium anomalies (Eu/Eu*) and orogen length big data database. The quantitative results indicate that the sustained orogens over 200 Ma formed prolonged super-mountains during the Gondwana assembly period. This might have occurred due to the initiation of modern type plate tectonic regime since the Neoproterozoic time, which allowed large-scale continental deep-subduction for the first time in Earth history. This coincides well with the large-scale Himalaya type collision orogenic belt during Gondwana assembly, along with the sudden drops of the global thermobaric ratio (T/P) and the large-scale occurrence of high-pressure and ultrahigh-pressure metamorphism. This suggests that orogenic elevation and scales were comparable to those of modern Earth. The high topographic relief of terrestrial systems during this time likely resulted in intense weathering and erosion of low-latitude orogenic belts, supplying huge continental sediments to the ocean, consistent with the seawater Sr isotope variation. Huge sediments and nutrients supply profoundly changed ocean composition and increased ocean productivity, triggering Neoproterozoic oxygenation events and providing environmental triggers for the Ediacaran–Cambrian explosion. Overall, multiple factors, with orogens being the most important one, contributed to the genetic, environmental and ecological conditions for Ediacaran life radiation and Cambrian life explosion.

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1. Introduction

The Neoproterozoic–Cambrian period was characterized by the initiation of modern plate tectonics (Brown M et al., 2020; Cawood PA, 2020; Stern RJ, 2020; Yao JL et al., 2021), as well as the supercontinent cycle from the breakup of Rodinia to the assembly of Gondwana (Gray D et al., 2008;

Meert JG and Lieberman BS, 2008; Nance RD et al., 2014; Oriolo S et al., 2017; Schmit RdS et al., 2018; Yao JL et al., 2019; Merdith AS et al., 2021; Mitchell RN et al., 2021). Meanwhile, the Earth's surficial systems also witnessed tremendous changes, including major extreme events such as the Cryogenian Snowball Earth and Neoproterozoic Oxidation Event (NOE) (Fig. 1; Och LM and Shields-Zhou GA, 2012; Lyons TW et al., 2014; Huang KJ et al., 2016; Hoffman PF et al., 2017), along with Ediacaran life radiation and the Cambrian explosion which ultimately established the metazoan-dominated ecosystems (Shu DG et al., 1999; Zhang XL and Shu DG, 2014; Knoll AH and Nowak MA, 2017; Darroch SAF et al., 2018; Wood R et al., 2019; Shu DG and

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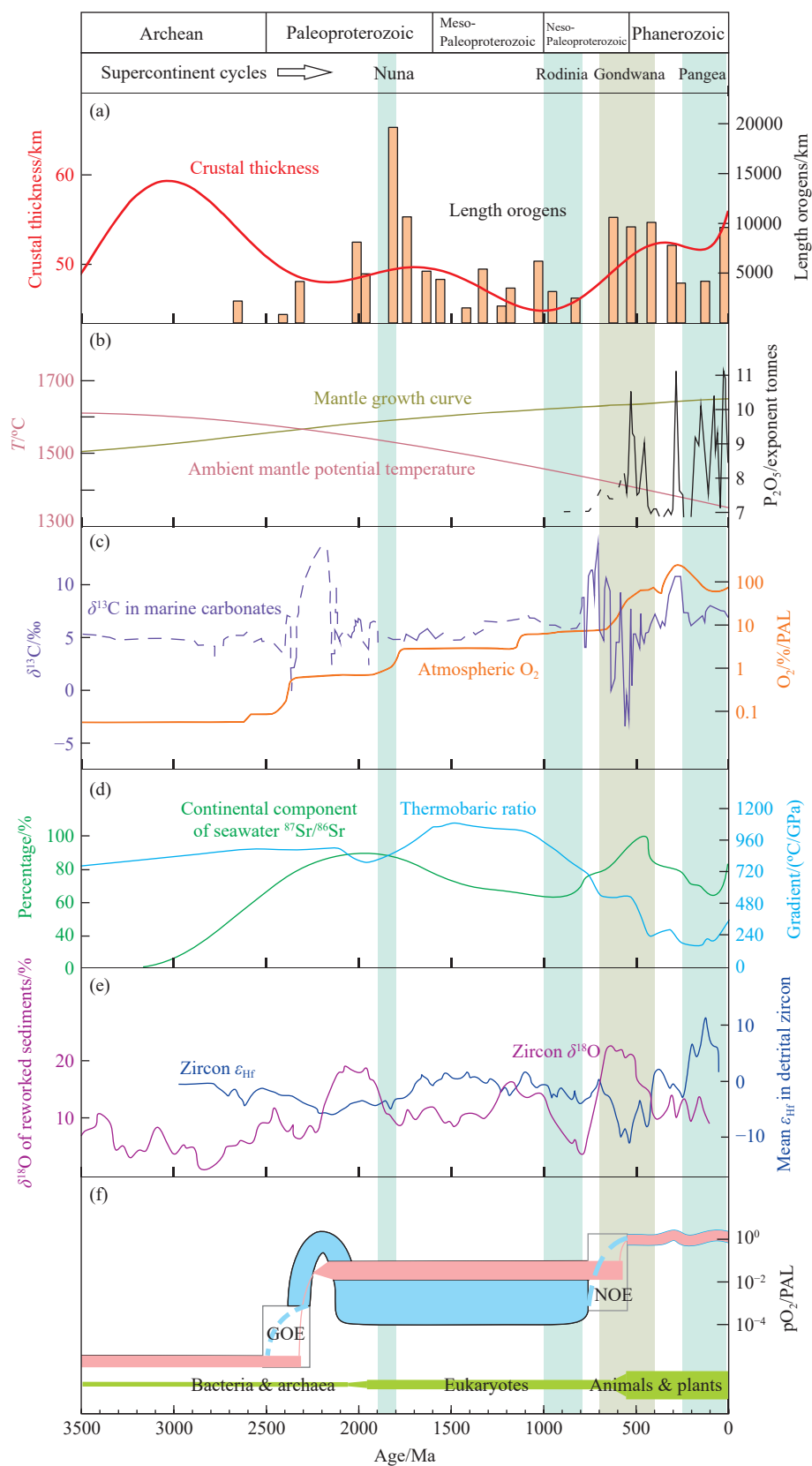


Fig. 1. Variation of Earth's multi-layer evolution indexes with time (modified from Campbell IH and Allen CM, 2008; Yao JL et al., 2021). a—Scale of orogeny encompassing both crust thickness and orogenic length; b—ambient mantle temperature, mantle growth curves, P₂O₅ content in phosphorites; c—δ¹³C in marine carbonates and atmospheric O₂ levels; d—⁸⁷Sr/⁸⁶Sr ratios in seawater-derived components and thermobaric ratio curve; e—the running mean of initial ε_{Hf} in detrital zircons and the running mean of zircon δ¹⁸O normalized to average sediment; f—trends in oxygenation events and changes in biodiversity.

Han J, 2020). Therefore, the Gondwana assembly period recorded crucial evolution of both Earth's tectonic regime and

habitability, serving as an important window for exploring the links between tectonic regime and Earth System Science.

However, the driving mechanism between tectonics and Earth surficial systems remains a subject of significant debate (Coltice N et al., 2019; Sobolev SV and Brown M, 2019), warranting further in-depth study.

Tectonic factors responsible for the occurrence of major extreme events during the Late Neoproterozoic to Cambrian time are mostly limited to conceptual models, including ‘plate tectonics-driven large-scale orogeny’, ‘supercontinent breakup and mantle plume activity’, and ‘tectonic degassing’ (Campbell IH and Allen CM, 2008; Li ZX et al., 2013; Cawood PA et al., 2016; Cox GM et al., 2016; Hoffman PF et al., 2017; Williams JJ et al., 2019; Yao JL et al., 2021), which are largely varied and merit further in-depth investigation. The mantle plume model argues that mantle plume activity associated with the breakup of Rodinia led to extensive continental flood basalt eruptions (Santosh M et al., 2014; Horton F, 2015; Cox GM et al., 2016; Gernon TM et al., 2016), which were enriched in P, Fe, and more susceptible to weathering and erosion, and thus ultimately enhanced oceanic primary productivity, thereby triggering atmospheric and oceanic oxygenation events. Additionally, the weathering of mafic rocks rapidly consumed atmospheric CO₂, leading to the onset of the Cryogenian Snowball Earth (Kennedy M et al., 2001; Cox GM et al., 2016; Hoffman PF et al., 2017). However, available data indicate that mantle plume magmatism was quite limited during the Late Neoproterozoic–Cambrian time (Li Z X et al., 2013; Ernst RE et al., 2021). On the other hand, the orogenic-driven model suggests that the establishment of modern plate tectonics during the assembly of Gondwana led to the unprecedented formation of large-scale orogenic belts (Campbell IH and Squire RJ, 2010; Yao JL et al., 2021). These long-duration, low-latitude super-mountains may have induced substantial levels of continental weathering and erosion, transporting a significant amount of nutrient elements to the oceans, which altered marine composition, enhanced oceanic productivity and sequestered organic carbon (Campbell IH and Squire RJ, 2010; Shields GA et al., 2019; Yao JL et al., 2021). This in turn promoted atmospheric oxygenation and provided a catalyst for the diversification of life. In addition, recent studies have proposed that during the Late Neoproterozoic to Cambrian, subduction-zone arc magmatism enhanced the rate of arc-magma degassing and CO₂ emissions (Mills BJW et al., 2017), which was sufficient to trigger atmospheric oxygenation (Williams JJ et al., 2019). But these models are mainly conceptual models, and the debate lies in the lack of a long-term quantitative characterization of tectonic and magmatic processes, which limits the exploration of the comparative and coupling mechanisms between solid Earth processes and surficial processes.

Given that the prolonged Gondwana super-orogens was the most significant tectonic event at that time, the authors here established the temporal variation of continental crust thickness based on zircon Eu anomaly big database. We believe that modern like crust thickness of about 50 km during Gondwana assembly, along with modern like

continental-ocean duality, contributed to unprecedented weathering-erosion and sediment supply to the oceans from the widespread collision-related low-latitude orogenic system. This significantly enhanced primary ocean productivity and ultimately changed seawater components, and in turn triggered the NOE and the Cambrian life explosion.

2. Methods

Determination the paleo-elevation of ancient mountain systems is based on the correlation of crustal thickness and topographic uplift (Elez J et al., 2020; Zhao ZB et al., 2021), such that higher mountains have deeper roots whereby the mountain roots provide buoyancy. Thus, crustal thickness is positively correlated to surface elevation (Airy GB, 1855; Pratt JH, 1855; Bowie W, 1926; Gratton J, 1989). The authors quantified paleo-elevation (E) from crustal thickness (H), as based on the Airy isostasy principle: $E = H \times (\rho_m - \rho_c) / \rho_m$ where $\rho_m = 3300 \text{ kg/m}^3$ (mantle density) and $\rho_c = 2800 \text{ kg/m}^3$ (average crustal density) (Elez et al., 2020). This is equivalent to $E \approx 0.15H$. For example, a crustal thickness of 50 km corresponds to a paleo-elevation of about 7.5 km, consistent with modern Himalayan peaks (Zhao ZB et al., 2021). In addition, uncertainty of $\pm 0.5 \text{ km}$ arises from density variations ($\pm 100 \text{ kg/m}^3$).

Considering that the proxy of zircon Eu anomalies as a crustal thickness proxy have been debated (Yakymchuk C et al., 2023), the authors effectively remove high-SiO₂ zircons. But for the Phanerozoic systems, Eu/Eu* remains valid when calibrated with metamorphic P–T data. Reliable methods for paleo-elevation estimation are largely based on geochemical ratios, and zircon Eu anomalies have been widely applied to reconstruction of crustal thickness (Tang M et al., 2021), especially in paleo-orogens where whole rock geochemical data are not available.

This study here employed the zircon Eu anomaly method (McKenzie NR et al., 2018; Tang M et al., 2021) to estimate crustal thickness based on the Global Zircon Database (Puetz SJ et al., 2024). To better reconstruct crustal thickness, zircons sourced from S-type granites or with inclusions have been filtered based on criteria of $P > 750 \times 10^{-6}$ and $La > 1 \times 10^{-6}$, respectively (Tang M et al., 2021). Metamorphic zircons were discarded based on screening criteria of $Th/U < 0.1$. Fig. 2 illustrates the trends in crustal thickness evolution obtained from zircon Eu anomalies.

3. Discussion

3.1. Quantitative reconstruction of orogens in Earth history

Super-orogens are defined here as orogenic systems characterized by both exceptional crustal thickness ($>50 \text{ km}$) and linear scales exceeding 8000 km in length. These features emerged during the Gondwana assembly due to whole plate deep continental subduction under modern plate tectonics, distinguishing them from earlier Precambrian orogens in terms of duration (persisting $>200 \text{ Ma}$), metamorphic regimes

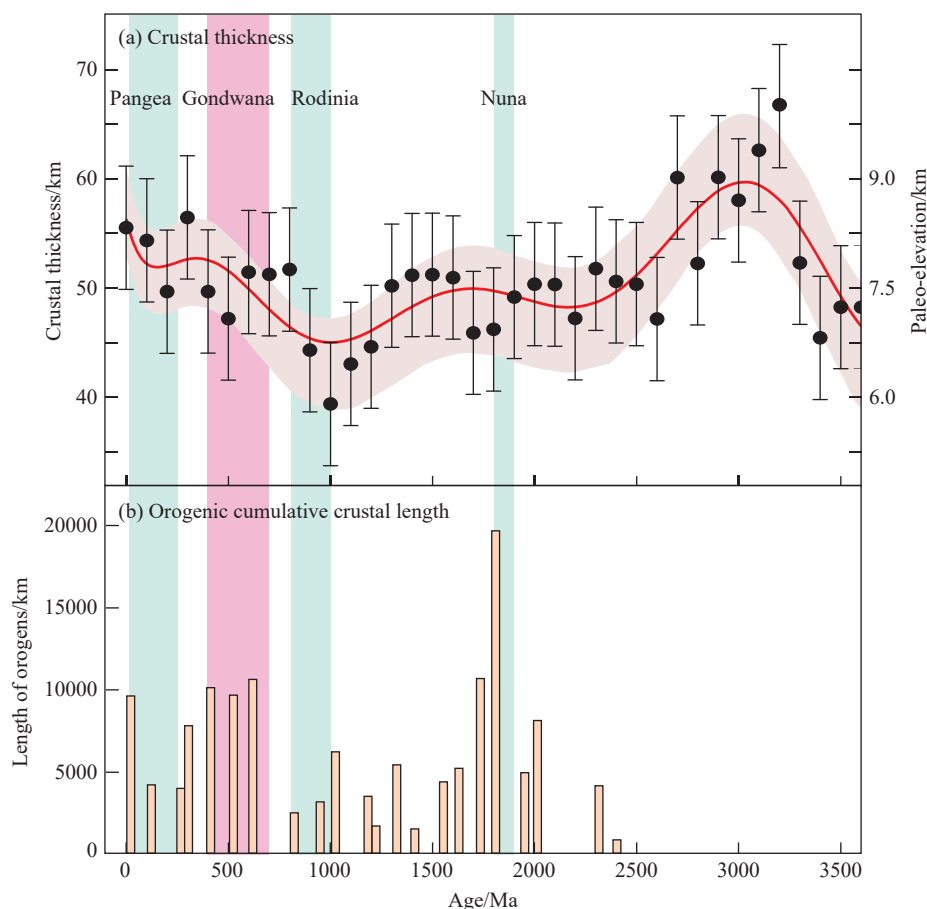


Fig. 2. Reconstructed orogenic scales (modified from Sobolev SV and Brown M, 2019). a–Trend of reconstructed crustal thickness based on zircon Eu/Eu* ratios. Black dots: Individual zircon Eu/Eu* measurements converted to crustal thickness. Error bars reflect 1σ analytical uncertainty. Red curve: 50 Ma moving average. Light red band: 95% confidence interval of the moving average, calculated by bootstrap resampling (1000 iterations); b–accumulated length of orogenic belts.

(widespread ultra-high-pressure eclogites), and surficial impacts (enhanced weathering and nutrient fluxes). A key characteristic that distinguishes Earth from other rocky planets in the solar system is the duality of oceanic and continental crust. The continental-oceanic configuration controls the Earth's surface elements cycling and is a crucial factor in forming surface environment, both for terrestrial and marine ecosystems. The existence of this duality is due to the significant variations in surface elevation and a bimodal distribution of oceanic and continental crust (Tang M et al., 2024). Airy isostasy principle argues that the higher the mountain, the deeper its root (Airy GB, 1855; Pratt JH, 1855; Bowie W, 1926; Gratton J, 1989), given that the crust density is lower than that of the underlying mantle. On the present Earth, continents are largely exposed above sea level because the thickness of the continental crust far exceeds that of the oceanic crust. However, recent studies indicate that surface elevation is limited, due to the fact that crustal thickening might lead to eclogitization in the lower crust and thus generate a high-density lower crustal root with a density greater than the mantle and limit further elevation increase (Tang M et al., 2024). For instance, in the Andes of South America, when crustal thickness exceeds about 60 km, the elevation stabilizes at around 4 km, even slightly decreasing

with further crustal thickening (Tang M et al., 2024). Similar phenomena have also been observed in the Qinghai–Xizang Plateau and the Ural Mountains (Zhao ZB et al., 2021). Petrologic phase equilibrium modeling results show that a depth of 60 km corresponds to the widespread phase change to eclogite in lower crustal rocks (Tang M et al., 2024).

This study employed zircon Eu/Eu* to obtain trends in crustal thickness changes, which reveal a trend of crustal thickening during the supercontinent assembly period (Fig. 2), consistent with widespread global scale orogens associated with supercontinent assembly (Zhao GC et al., 2002; Tang M et al., 2020; Yao JL et al., 2021). Despite thicker crust in the Mesoarchean, the Nuna super-orogen lacked the duality of continental and oceanic crust and low-latitude positioning of Gondwana, limiting its surficial impacts.

Notably, during the Late Neoproterozoic–Cambrian period, crustal thickness reached an average of 50–60 km, consistent with the modern average crustal thickness. This implies paleo-elevations of 7.5–9.0 km in collisional orogens. These values exceed most Precambrian orogens (<6 km) and match modern Himalayas, confirming unprecedented topographic relief (Tang M et al., 2021). This indicates that during the Gondwana assembly period, the global orogenic belt heights were close to those of modern orogenic belts (Fig.

2a). Although the global average crustal thickness today is about 40 km (Christensen NI and Mooney WD, 1995), this study reconstructed values (about 50 km) align with modern orogens rather than stable cratons. This highlights that the Gondwana super-orogens achieved crustal thicknesses comparable to the thickest modern mountain belts, driving uniquely intense weathering-erosion. Furthermore, previous statistical results on big datasets show that during the Gondwana assembly period, the lengths of orogenic belts were comparable to present Earth (Fig. 2b; Sobolev SV and Brown M, 2019). Therefore, the scale of global orogenic belts formed during the Gondwana assembly period was similar to modern orogenic one, significantly higher than that of the preceding Rodinia supercontinent and the subsequent Pangaea supercontinent (Fig. 2).

The obtained orogenic trend is well-supported by metamorphic big data, which indicates a significant decrease in Earth's temperature-pressure (T/P) ratio during Gondwana assembly (Fig. 1d). This might indicate large-scale subduction due to the initiation of modern plate tectonics (Holder RM et al., 2019; Brown M et al., 2020; Edgar A et al., 2022). For example, the ultra-high-pressure eclogites from the Altyn orogenic belt (about 500 Ma) report the presence of stishovite, indicating peak metamorphic pressures of 8–9 GPa and suggesting subduction depths of up to 300 km (Liu L et al., 2018). This is comparable to coesite and stishovite within diamonds in the Himalayas (Yang JS et al., 2007; Geng Y et al., 2018). Additionally, multiple worldwide Gondwana orogenic belts have reported coeval ultra-high-pressure metamorphism, such as the diamond-bearing high-pressure metamorphic rocks along the Gondwana-Pacific margin in the Antarctic orogenic belt and the metamorphic garnet grains containing coesite inclusions within the Ordovician metamorphic sediments along the Clark River Fault in northeastern Queensland (Edgar A et al., 2022). Therefore, the appearance of large-scale orogenic belts during this time largely resulted from the emergence of modern plate tectonic regimes on Earth, triggering deep-subduction (Sizova E et al., 2014; Yao JL et al., 2021).

The super mountains during Gondwana assembly also coincide well with zircon Hf isotopes that reached the lowest in Earth's history, while O isotopes reached the highest (Fig. 1e; Condie KC et al., 2016; Spencer CJ et al., 2017; Brown M et al., 2020). This indicates that the largest-scale crustal recycling in Earth's history occurred during the Gondwana assembly period. This is entirely consistent with the widespread continental deep-subduction during the Gondwana assembly period, indicating the formation of unprecedented Himalayan-type continent-continent collision orogenic belts, triggering a global-scale continental crust recycling.

During the Gondwana assembly, multi-stage orogenic movements occurred. The East African Orogeny (800–650 Ma) led to the formation of the Mozambique Belt, resulting in the collision of India, Madagascar, and Sri Lanka with East Africa. The Brasiliano Orogeny (600–530 Ma) amalgamated of the South American and African. The 530–520 Ma

Kuunga-Damara Orogeny recorded the collision of Australia and Antarctica with other parts of Gondwana, whereas the Damara Belt eventually collided with the Kalahari–Antarctic craton, completing the final assembly of Gondwana (Fig. 3; Gray D et al., 2008; Meert JG and Lieberman BS, 2008; Schmitt RdS et al., 2018). The convergence of the East Asian blocks occurred significantly younger, at 500–420 Ma, with the closure of the Proto-Tethys Ocean leading to the amalgamation of South China, North China, Alxa, Qaidam, and Tarim blocks to the northern margin of Gondwana (Zhao GC et al., 2018). Therefore, the East African Orogen, Kuunga Orogen, Brasiliano-Damara Orogen, and East Asian Orogen were the principal orogenic belts that amalgamated the Gondwana landmasses (Meert JG and Lieberman BS, 2008; Yao JL et al., 2021), with lengths reaching up to 9000 km (Fig. 2). Thus, the total orogenic scale was unprecedented on Earth (Table 1). Furthermore, oceanic crust thinning has intensified, increasing the duality of continental and oceanic crust, and formation of modern like topography during the Gondwana assembly (Fig. 4). The evolution of Earth's topography hence entered a new phase since that time. These super-mountains, which rose significantly above sea level in mid to low latitudes, were exposed to intense monsoonal precipitation (Fig. 3), amplifying chemical weathering rates by 3–5 times compared to high-latitude regions (Riebe CS et al., 2004), greatly enhanced continental weathering and erosion, providing a substantial sediment supply to the oceans and subduction zones.

3.2. Super-orogens during the Gondwana assembly led to extensive weathering and erosion

In the early Earth time, due to the excessively high mantle temperatures and less continental-oceanic duality, the continental crusts were largely submerged below sea level (Tang M et al., 2024), leading to lower weathering rates and less delivery of nutrients to the oceans. This limited the rate of oxygen production (Van Thinenen P et al., 2004; Höning D and Spohn T, 2016; Korenaga J, 2018). However, this was largely changed since the time of Gondwana assembly, with modern like ocean and continental crust duality and super mountains, intensifying erosion and orogenic weathering and further improving the rate of oxygen production. These orogenic belts were predominantly located in the mid to low latitudes monsoon zones triggered extensive weathering (Fig. 3), thus significantly enhancing continental weathering and erosion (Shields-Zhou GA and Och LM, 2011). Notably, continental weathering serves as a crucial link between tectonic processes and bioenvironmental evolution, playing a significant role in Earth evolutionary history (Yuan XP et al., 2024). Quantitative models of sediment flux reveal a positive correlation between continental erosion rates and marine biodiversity during the Ediacaran–Cambrian transition (Fig. 5), supporting the hypothesis that tectonic-driven sediment supply was a key external driver of ecosystem evolution (Salles T et al., 2023).

During the Neoproterozoic–Cambrian period, continent-

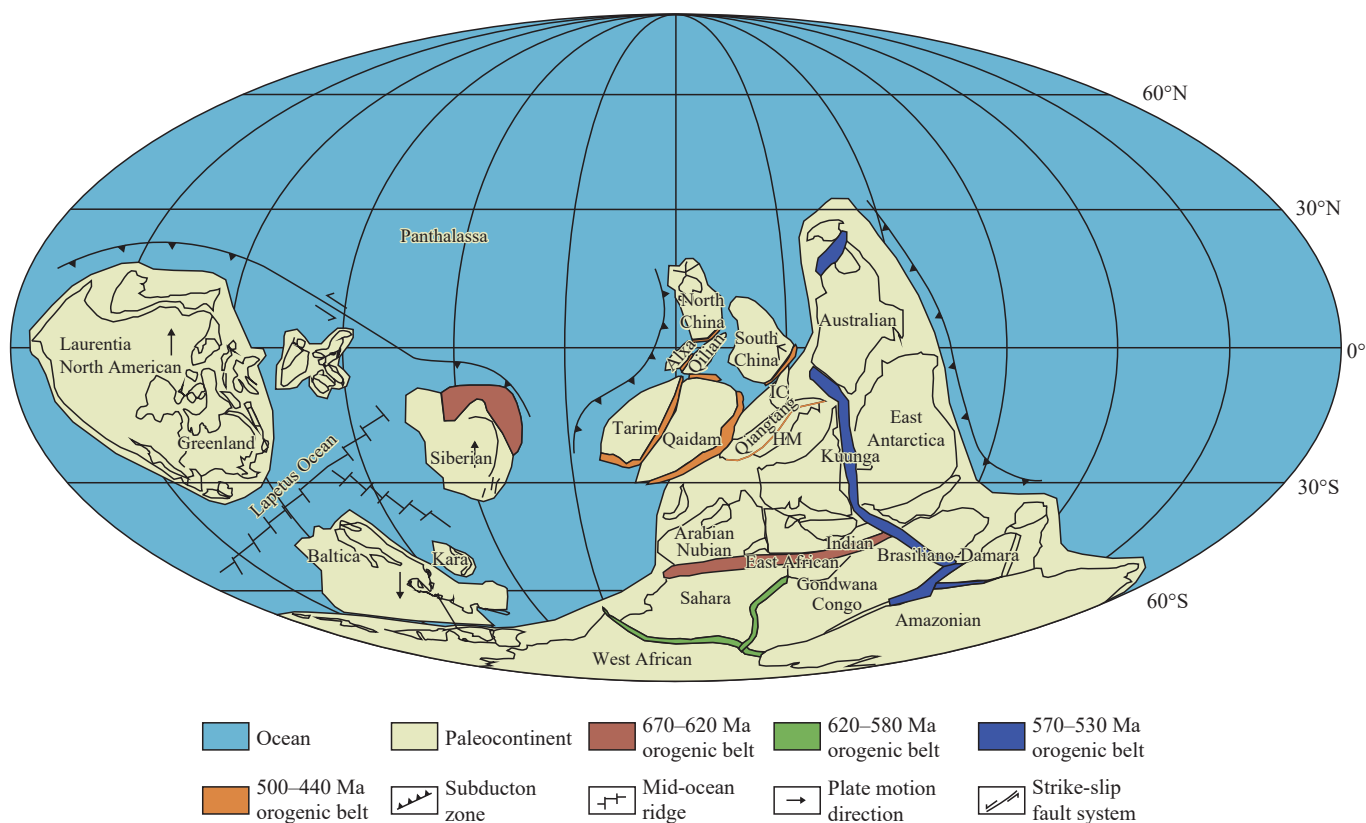


Fig. 3. Reconstruction of Gondwana (modified from Cawood PA et al., 2021; Yao JL et al., 2021).

continent collisions formed super-mountains that led to the exposure and intense erosion of continental rocks (Campbell IH and Allen CM, 2008), further increasing the rate of chemical weathering. The enhanced chemical weathering caused a dramatic increase in the delivery of nutrients to the oceans. This is consistent with the significant rise in the $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of seawater during the Neoproterozoic–Early Paleozoic time, reaching the highest values in Earth’s history during this period (Fig. 1d; Shields GA, 2007; Bednarick AL et al., 2024). This indicates that the super orogens and revolutionary changes in differentiation of land-sea topography during the Gondwana assembly resulted in substantial continental weathering and transported sediments into the marine system. Furthermore, the intensified burial of organic matter further drove changes in oceanic composition and increased ocean productivity, as well as the oxidation of Earth’s surface environment.

3.3. Tectonic factors responsible for Earth System Revolution during Gondwana supercontinent cycle

Tectonic factors associated with significant surficial extreme events are highly debated, with conceptual models including ‘plate tectonics-driven large-scale orogeny’, ‘supercontinent breakup and mantle plume activity’, and ‘tectonic outgassing’ (Campbell IH and Allen CM, 2008; Li ZX et al., 2013; Cawood PA et al., 2016; Hoffman PF et al., 2017; Yao JL et al., 2021). It is noteworthy that large igneous provinces (hips) was scarce between 710–500 Ma (Lyons TW et al., 2014). Moreover, high sea level and deep-water

sedimentation during the Rodinia breakup argue against the major contibution of large igneous provinces to oxygenation process and multi-episodic environmental changes (Ernst RE et al., 2021). Instead, here this study concluded that the LIPs related to the breakup of Rodinia at 820–700 Ma triggerred surfical changes, but super orogens during Gondwana assembly contributed to sustained evolution.

Indeed, the weathering of basalt consumed atmospheric CO_2 , leading to a decrease in CO_2 concentrations and triggering the occurrence of Snowball Earth events (Kennedy M et al., 2001; Cox GM et al., 2016; Hoffman PF et al., 2017). Concurrently, increased input of P into the oceans and enhanced primary productivity led to the onset of atmospheric oxygenation (Fig. 6; Li ZX et al., 2013; Horton F, 2015; Cox GM et al., 2016; Gernon TM et al., 2016; Hoffman PF et al., 2017; Zerkle AL, 2018; Lyons TW et al., 2021). The weathering effects of these LIPs peaked in the mid-Neoproterozoic and then rapidly declined, which closely corresponds to the changes in the carbon isotope ratios of seawater and the timing of Snowball Earth events, suggesting that the weathering of large igneous provinces is an important triggering factor for the Neoproterozoic oxygenation events (Cox GM et al., 2016; Gernon TM et al., 2016; Hoffman PF et al., 2017).

Since 670 Ma, the prolonged subduction-accretion orogenesis and associated arc magmatism, as well as collisional orogenic belts during the Neoproterozoic–Early Paleozoic, may have been the primary drivers of Earth’s oxygenation. The Gondwana assembly led to the formation of super-mountains, triggering intense physical and chemical

Table 1. Data compilation of Gondwana post-670 Ma orogens (modified from Schmitt RdS et al., 2018).

Time	Continent	Name
670–620 Ma	South America	Ribeira Belt–Paralba/Embu/Apiaf Terranes
		Dom Feliciano Belt
		Brasilia Belt (North and South)
	Africa	Arabian Nubian Shield–North and South
		Mozambique Belt
	Antarctica	Kaoko Belt–Coastal Terrane Dronning Maud Land–SRM and YBCa
620–580 Ma	South America	Ribeira Belt–Cabo Frio Tectonic Domain
		Araçuaí Belt–West
		Nico Perez Terrane
		Borborema Province–North
	Africa	Borborema Province–Central
		Ad Dawadimi and Ar Rayn Terranes
		Vohibori/Androyen
		Domains–Madagascar
		Hoggar
		Dahomey
		West Congo Belt
		Rokelides Belt
		Bemarivo Belt–Madagascar
		Antananarivo Block–Madagascar
570–530 Ma	Africa	Lufilian Belt
		Zambesi Belt
		Angolan Belt
		Damara Belt
		Kaoko Belt–Central East
		Gariiep Belt
		Anti–Atlas Belt
		Rokelides Belt
		Saldania Belt
		Galana Terrane
		Western Granulites
	India	Western Granulites
		Southern Granulite terrane
	Antarctica	Eastern Ghats Mobile Belt
		Dronning Maud Land (West)
		Prince laf Coast/Kemp Land–Lutzow–Holm Complex
		Ross Orogeny–Pensacola Mountains
	Australia	Petermann Orogen
		Pinjarra Orogen
500–440 Ma	Africa	Mozambique Belt–Nampula Block
		Princess Elizabeth Land
	Antarctica	Ross Orogeny–North Victoria Land
		Ross Orogeny–South Victoria Land
	Australia	Delamerian Orogen

weathering, and releasing large amounts of nutrients such as Fe and P into the oceans. These nutrients promoted the explosive growth of algae and bacteria, enhancing photosynthesis and significantly increasing oceanic oxygen levels. High sedimentation rates during continental collision improved the burial of organic carbon and pyrite, leading to a

continuous increase in atmospheric oxygen levels (Fig. 6a; Squire RJ et al., 2006; Campbell IH and Allen CM, 2008). Geological records indicate that large-scale orogenesis during the Gondwana assembly coincided well with the timing of the NOE. Major Earth tectonic events during this period are considered significant drivers of the oxygenation event and the Ediacaran–Cambrian explosion, profoundly altering the global marine ecosystem (Knoll AH and Nowak MA, 2017). Hence, the orogenic-driven model can reasonably account for the environmental changes during the Gondwana amalgamation phase (680–500 Ma) (Meert JG and Lieberman BS, 2008). On the other hand, large-scale subduction-accretion orogenesis is the primary carbon source for geological scales, releasing carbon from carbonates through magmatic degassing in subduction zones, making it one of the key geological processes with a decisive impact on Earth's carbon cycle (Fig. 7). The Gondwana assembly process, with its extensive deep subduction, increased carbon emissions and further raised the temperature of Earth's surface (Mills BJW et al., 2017; Williams JJ et al., 2019). Elevated CO₂ levels acted both as a raw material for photosynthesis, with its increased levels aiding in enhancing photosynthetic efficiency, and as a greenhouse gas capable of raising surface temperatures, thus increasing biological activity and productivity. Therefore, the two types of orogenic belts during the Gondwana assembly period were the continuous key drivers of Earth's environmental changes during the mid-Neoproterozoic–Early Paleozoic.

In summary, the environmental changes and life evolution during the Neoproterozoic–Early Cambrian time involved the interplay of multiple geological processes. The Rodinia breakup triggered dramatic surficial changes, but the Gondwana super-orogens made sustained contribution to Neoproterozoic atmospheric oxidation and related environmental evolution (Fig. 6).

3.4. Global orogeny triggered the Ediacaran radiation and the Cambrian explosion

Topography and climate influence the formation of landforms, affecting erosion rates and physical-chemical-biological processes within Earth's critical zones. Therefore, within Earth's critical zones, there are often significant quantitative relationships between topography, lithology, climate, uplift rates, erosion rates, and the depth and intensity of weathering (Renschler CS et al., 2007). Early studies indicate that the increase in topography significantly accelerates denudation rates and enhances the rate of chemical weathering, thereby improving the efficiency of carbon sequestration (Riebe CS et al., 2004; Whitehead JA and Clift PD, 2009). The pronounced duality of continental and oceanic crust and large-scale orogenesis during Gondwana period significantly intensified continental weathering and erosion, accelerating the delivery of nutrient elements to the oceans and providing the material basis for the establishment of modern marine ecosystems (Fig. 4).

Among the many factors affecting biodiversity and ecosystems, the supply of nutrients is a key external driving force. Phosphorus is a limiting nutrient element that controls

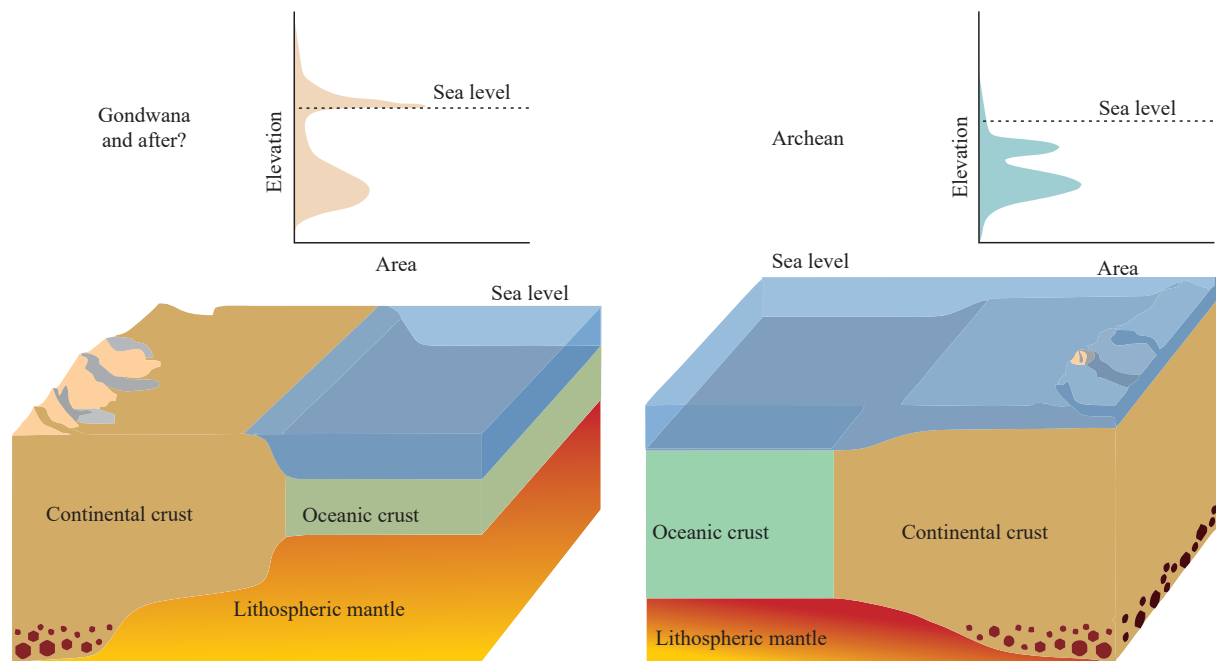


Fig. 4. Duality of continental and oceanic crust (modified from Tang M et al., 2024).

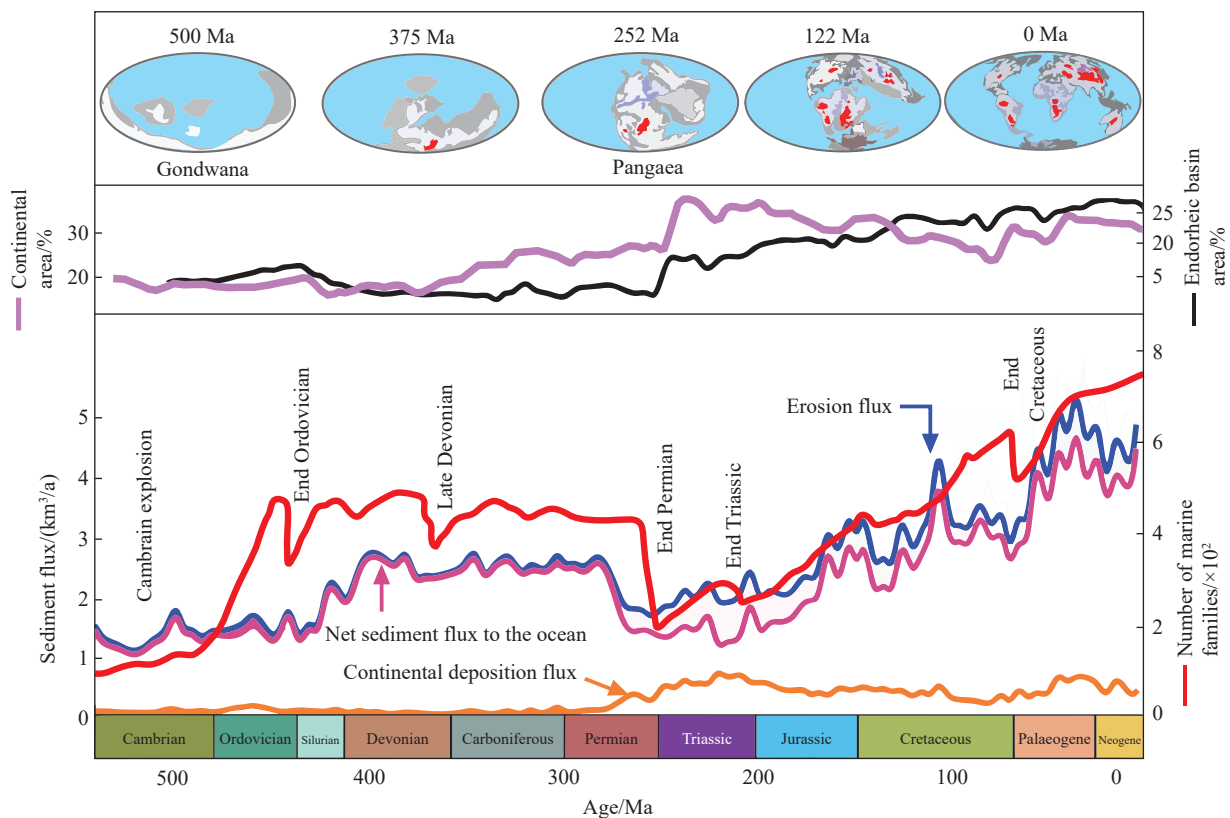


Fig. 5. Sediment flux and evolutionary patterns of biodiversity (modified from Salles T et al., 2023).

the oceanic oxidation level, there was an impulsive increase in oceanic phosphorus concentrations during the Ediacaran period (Fig. 1b; Zhao M et al., 2024), due to the release of CO_2 and P from sulfate oxidation of marine organic matter, as well as phosphorus released by carbon-dioxide-driven weathering on land (Dodd MS et al., 2023). Oxygen and phosphorus are essential for animal life activities. The

enrichment of nutrients in the marine environment leads to an increase in primary productivity, which is not directly related to biodiversity. Therefore, the impact of Gondwana assembly on biological evolution is exerted indirectly by changing atmospheric oxygen levels and marine chemical conditions (Zhang XL and Shu DG, 2014). Enhanced weathering can increase the concentrations of sulfate and phosphorus in the

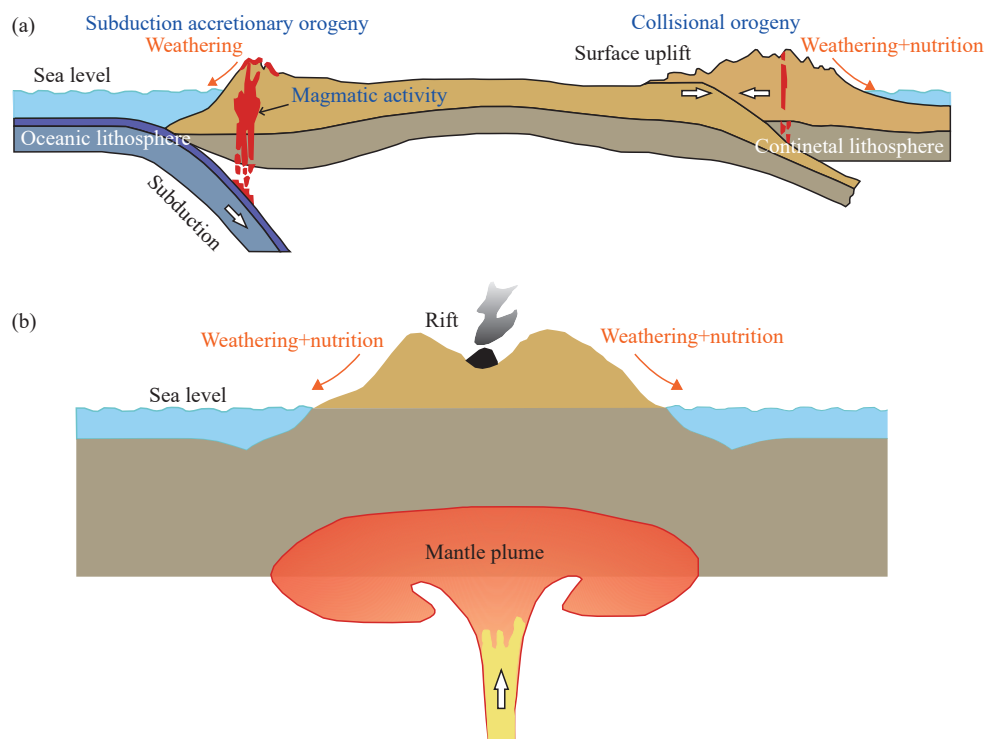


Fig. 6. Solid Earth drives the Earth's surface processes pattern diagram (modified from Santosh M et al., 2014).

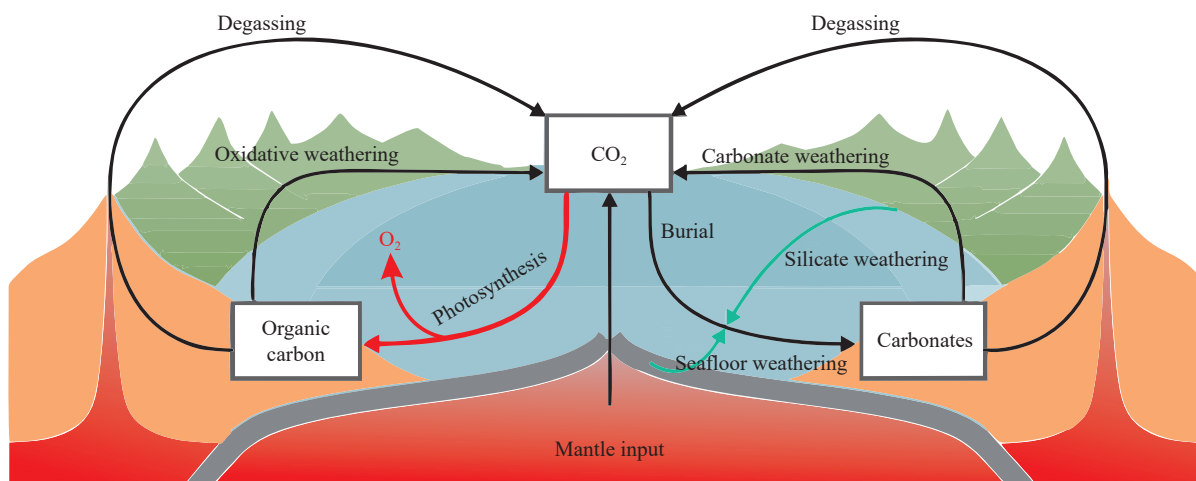


Fig. 7. Model representations of the carbon cycles (modified from Mills BJW et al., 2019).

oceans, thereby promoting marine oxidation and the evolution of life. Additionally, subduction zone magma degassing increases atmospheric CO₂ concentrations, while global orogeny increases the rate of rock weathering that reduce atmospheric CO₂ levels; the dynamic balance between these two processes determines the geological carbon cycle (Fig. 7). On one hand, they provide raw materials for photosynthesis, and on the other hand, they dictate Earth's temperature, affecting climate stability (Cao JH et al., 2018; Mills BJW et al., 2019), providing conditions for the Ediacaran radiation and evolution of life. Orogenic processes lead to changes in landscape, thereby affecting the carrying capacity of terrestrial and marine ecosystems and subsequently the evolution of biodiversity. During the Ediacaran Period, global orogeny resulted in significant alterations in the landscape,

offering new habitats and resources for early complex life, promoting their radiation. By the Cambrian Period, ongoing orogeny and landscape changes provided favorable conditions for more complex life forms, leading to the Cambrian explosion (Salles T et al., 2023).

During the Ediacaran–Cambrian transition period, the sustained oxidation of seawater and the increase in nutrient elements may have been key environmental factors driving the Cambrian explosion. Topographic uplift and fluctuations in sea level significantly impacted the diversity and distribution patterns of marine life. Additionally, orogenesis increased topographic complexity, creating new environmental gradients and geographic isolation, which promoted species adaptation and differentiation, ultimately leading to an increase in species diversity (Badgley C, 2010).

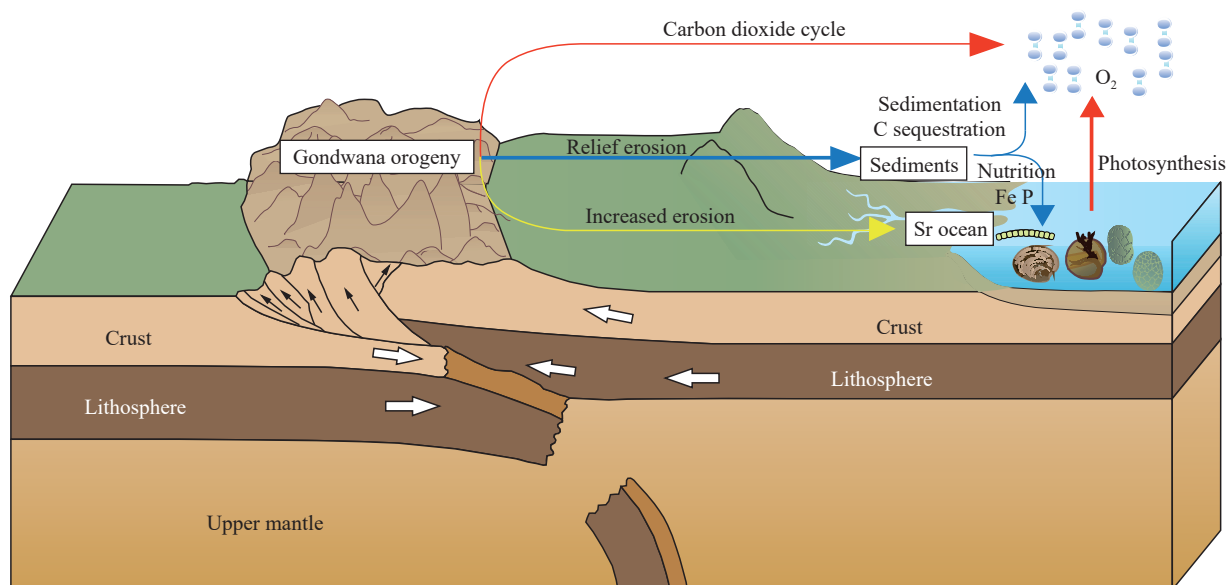


Fig. 8. Orogenic drives the Earth's surface processes.

In summary, the formation of large-scale orogenic through super-mountains has intensified the processes of weathering, erosion, and sedimentation. The increase in topographic elevation has a strong impact on the rate of denudation. The multiple stages of orogeny, accompanied by tectonic denudation and continental weathering, have supplied nutrients to the oceans, enhancing the oxygen content in the atmosphere and the oceans. Orogeny, by influencing the changes in oxygen levels in the atmosphere and the oceans, has thus triggered the Ediacaran–Cambrian Explosion (Fig. 8).

4. Conclusion

During the Gondwana supercontinent assembly, the formation of super-mountains exceeding 9000 km in length and persisting for 200 Ma under modern plate tectonic regimes provided the driving force for the evolution of surficial systems. This process coincided with a sharp decline in global temperature–pressure (T/P) ratios and the widespread occurrence of high-pressure–ultra-high-pressure metamorphism, indicating the establishment of modern plate tectonics during this period, leading to large-scale continental deep subduction. Moreover, the further significant expansion of the duality of continental and oceanic crust on Earth during this period resulted in unprecedented levels of topography, with widespread continental exposure, providing ecological niches for animal activities. The intense weathering and erosion triggered by these low-latitude orogenic belts supplied vast amounts of continental-margin sediments to the oceans. The influx of these sediments and nutrients profoundly altered the composition of the oceans and enhanced marine productivity, inducing oxygenation events, and providing environmental triggers for the Ediacaran radiation and the Cambrian explosion.

CRediT authorship contribution statement

Peng-yuan Cui, Jin-long Yao, and Guo-chun Zhao

conceived of the presented idea. Peng-yuan Cui and Jin-long Yao carried out the experiment. All authors discussed the results and contributed to the final manuscript.

Declaration of competing interest

The authors declare no conflicts of interest.

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