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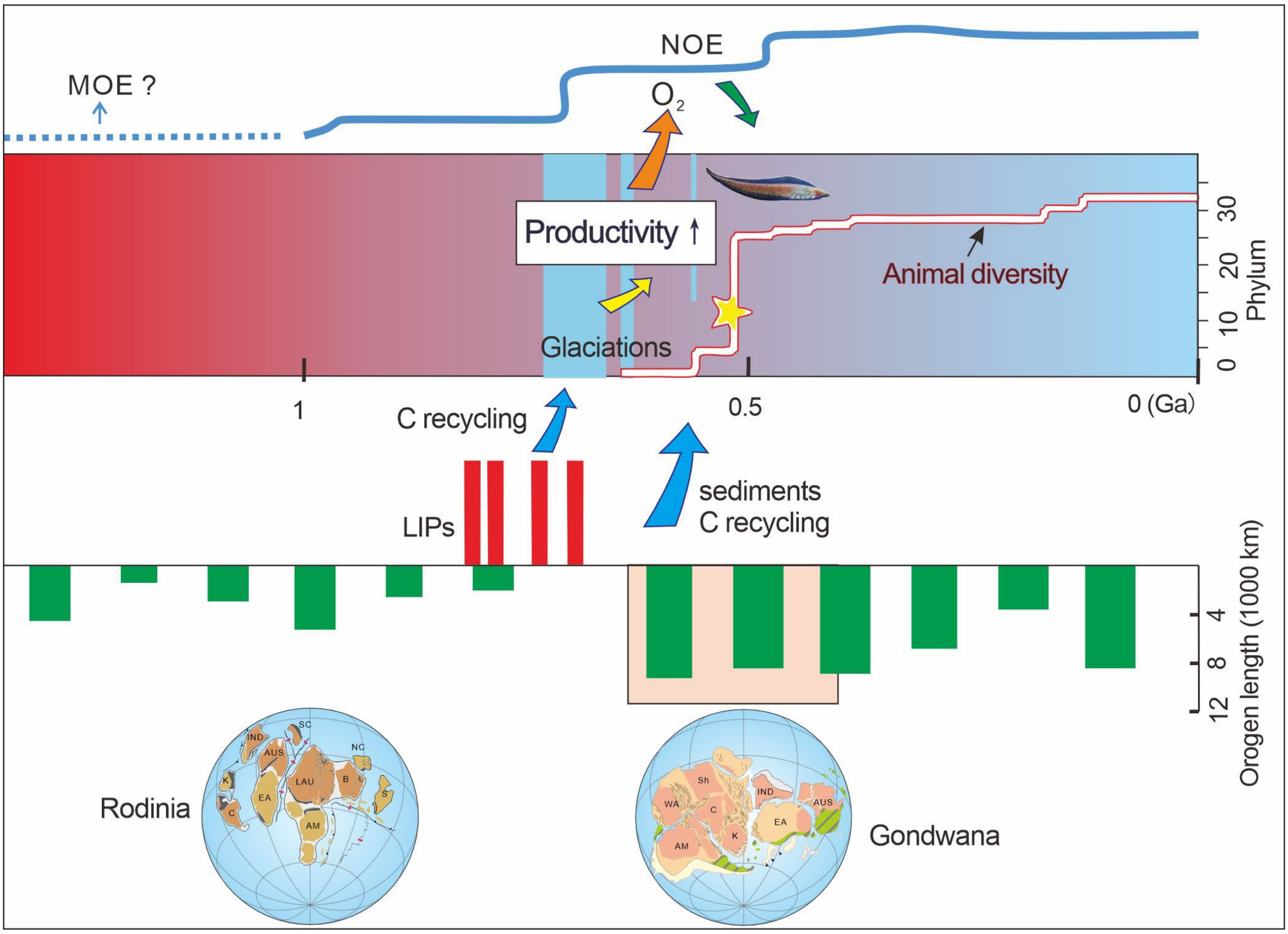
Graphical Abstract



Highlights:

- Tectonics and supercontinent cycles serve as primary driving forces for the evolution of Earth's habitability.
- Plate tectonics and mantle plume drive the exchange of elements and energy between different spheres.
- Coupled tectonic-environmental changes and geomagnetic field triggered the Cambrian explosion.

Material cycling across Earth's spheres and triggers of Cambrian explosion: a tectonic perspective

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Abstract: Earth is the only known planet in the solar system that can sustain and provide a habitable environment for life, largely due to the presence of stable but evolved oceans, continents, magnetic field, atmosphere, surface temperature, as well as exchange of elements and energy between different spheres of Earth that are driven by plate tectonics and mantle plume. Particularly, the Cambrian life Explosion is a milestone in Earth history, which overlapped with the Neoproterozoic oxygenation event (NOE), Gondwana assembly (~680–430 Ma) and the Snowball Earth events. Moreover, modern plate tectonics may have been established during this period as well. However, the tectonic factors that drove the evolution of surficial systems in this period are less well constrained. Here, a review of observation patterns shows that the chains of reactions initiated with the breakup of the Rodinia supercontinent, which triggered the Snowball Earth and Neoproterozoic oxygenation events. Meanwhile, Snowball Earth also contributed to continental weathering and oxidation event. The subsequent Gondwana assembly, within a modern plate tectonic regime, generated orogens that lasted for more than 250 million years. The topographic relief might have reached high level during this period, which can provide ecological space for ocean animal system. These super orogens served as a continuous driving force for the changes of Earth's surficial environs. This, together with low-latitude orogenic belts, caused extensive weathering and supplied huge continental sediments to the ocean, which profoundly changed ocean composition and increased ocean productivity, and sustained the NOE. In addition, Earth had an extremely weak magnetic field at E-C boundary, possibly related to the formation of the Earth's inner core and establishment of modern plate tectonics. Overall, tectonic processes provided the first order contribution to changes of environment that triggered the Cambrian life Explosion.

Keywords: plate tectonics; orogen; continental weathering; Cambrian explosion; Gondwana; Earth system

1. Introduction

The unique characteristics that distinguish Earth from other rocky planets in the solar system include life, plate tectonics, continental crust, and the bimodal distribution of continents and oceans, which comprises the fundamental elements of Earth habitability (Langmuir and Broecker 2012; Elkins-Tanton 2013). Earth habitability evolved largely due to the presence of stable but evolved oceans, continents, magnetic field, atmosphere and surface temperature, as well as exchange of elements and energy between different spheres of Earth (Figure 1; Xu *et al.* 2024; Yao *et al.* 2025; Zhu *et al.* 2025). Earth is the only known planet in the solar system that can sustain and provide a habitable environment for Life. Life probably appeared on Earth as early as 3.8 billion years ago (Dodd *et al.* 2017), and evolved from prokaryotes to eukaryotes and finally to Metazoans (Knoll and Nowak 2017; Zhang and Shu 2021; Zhang *et al.* 2023), which coincided with the formation of continental crust, and Nuna and Gondwana assembly, respectively (Figure 1).

Earth started as a magma ocean covered inhabitable planet, with atmosphere composition evolved from H_2 and He of the accretion stage to methane and ammonia dominated reducing environment of the magma ocean stage (Langmuir *et al.* 2012). Over geological history, tectonics and supercontinent cycles have continuously served as primary driving forces behind the formation of continent and exchange of elements among ocean and continents, and also surficial spheres and solid Earth (Figures 1, 2, 3; Campbell and Allen 2008; Li *et al.* 2013; Nance *et al.* 2014; Cox *et al.* 2016; Hoffman *et al.* 2017; Williams *et al.* 2019; Zhao *et al.* 2022; Cawood *et al.* 2022; Peng *et al.* 2025), which contributed to the evolution of Earth's surface environment. The driving mechanism triggered extreme events in the evolution of life and environs, and ultimately shaped a habitable planet with oxidized ocean and atmosphere, and also biodiversity (Campbell and Squire 2010; Elkins-Tanton 2013; Brune *et al.* 2017; Mills *et al.* 2017; Tang *et al.* 2021; Yao *et al.* 2021a; Zhu *et al.* 2021), which has become the focus of international geosciences. These advances also have broad implications for understanding natural hazards, resource distribution, environmental change, climate evolution, and the development of planetary habitability (Xu *et al.* 2024; Zhao *et al.* 2022; Zhu *et al.* 2025; Ding *et al.* 2026). However, how Earth evolved from an inhabitable hot planet in its early stage into a habitable planet with a well-structured multi-sphere system, a thriving biosphere and a sustained environment, is poorly constrained (Elkins-Tanton 2013; Wang *et al.* 2018; Shahar *et al.* 2019; Xu *et al.* 2024), which remains a major scientific debate in the field of Earth science.

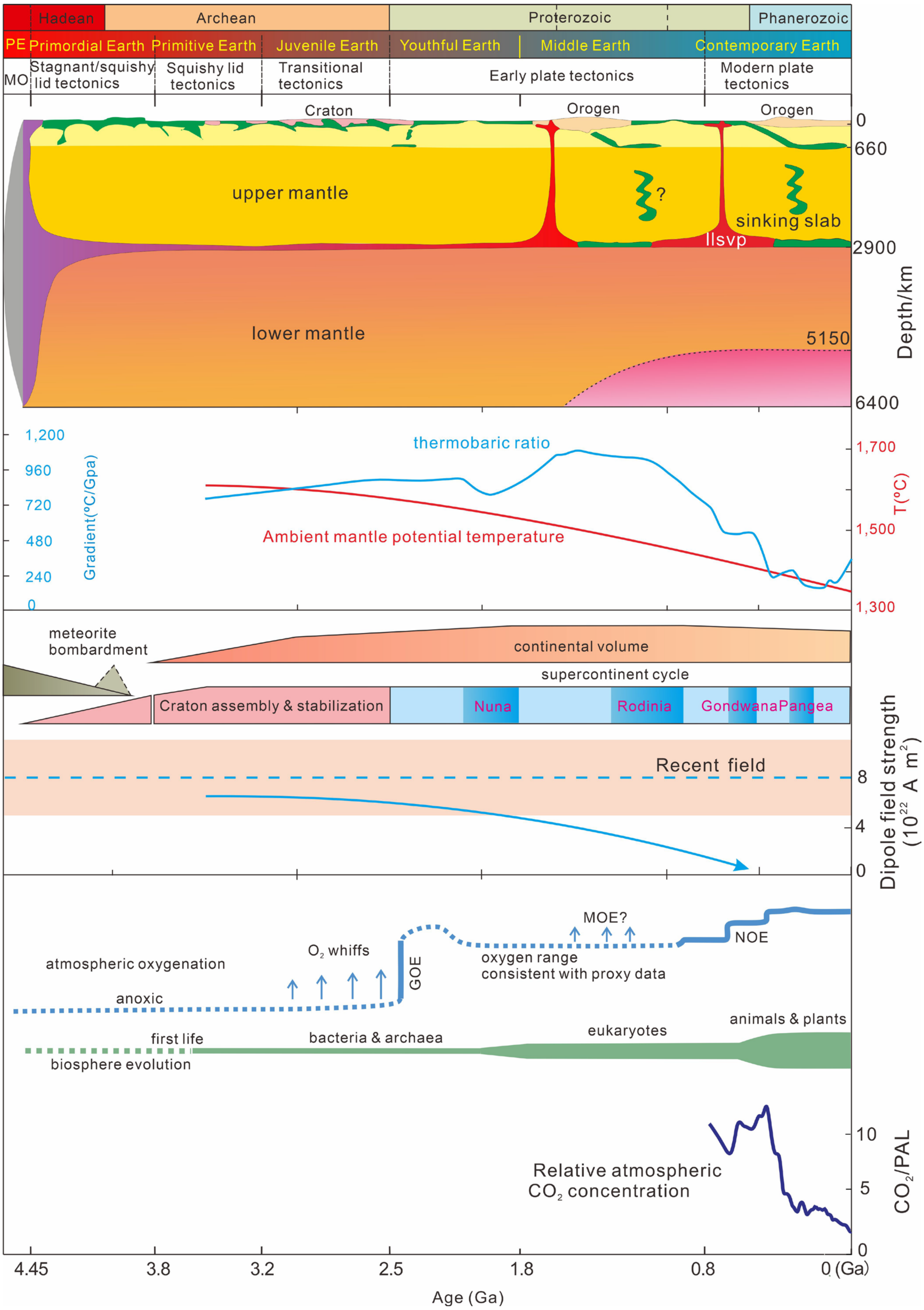

Figure 1. Evolution of Earth's geological and surficial proxies (revised after Bono *et al.* 2019; Yao *et al.* 2025; Cawood *et al.* 2022).

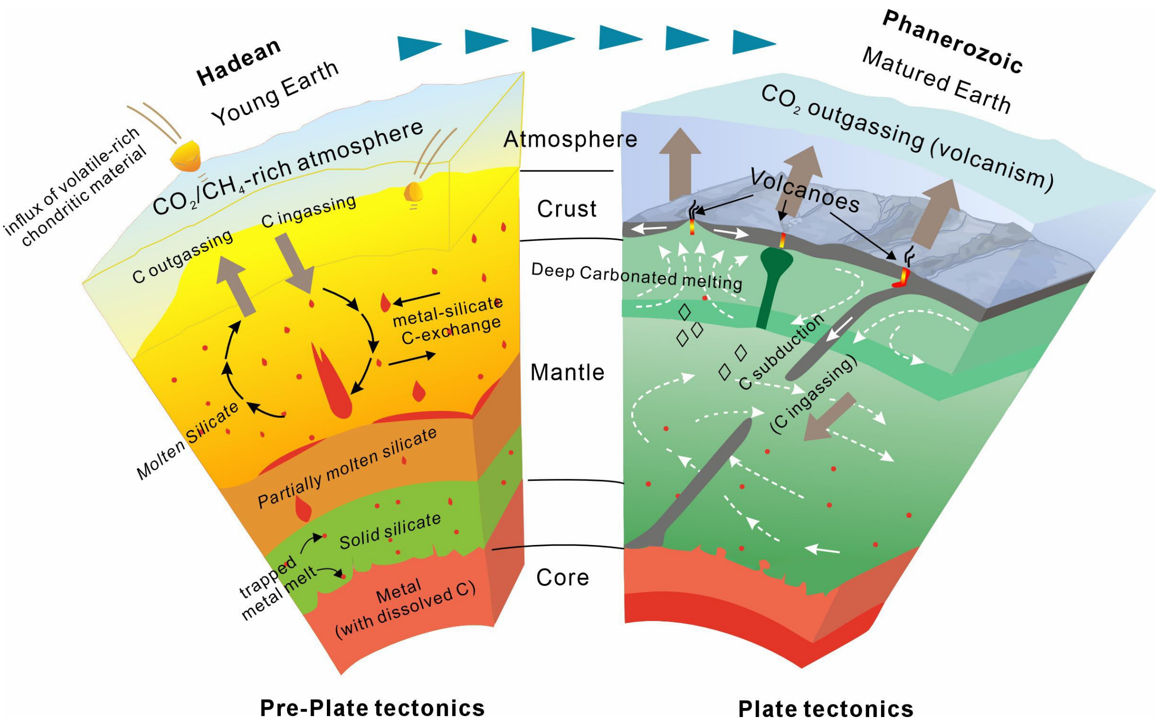

Figure 2. The deep-Earth processes from magma ocean stage to plate tectonics that dominated the long-term carbon cycle (revised after Dasgupta 2013).

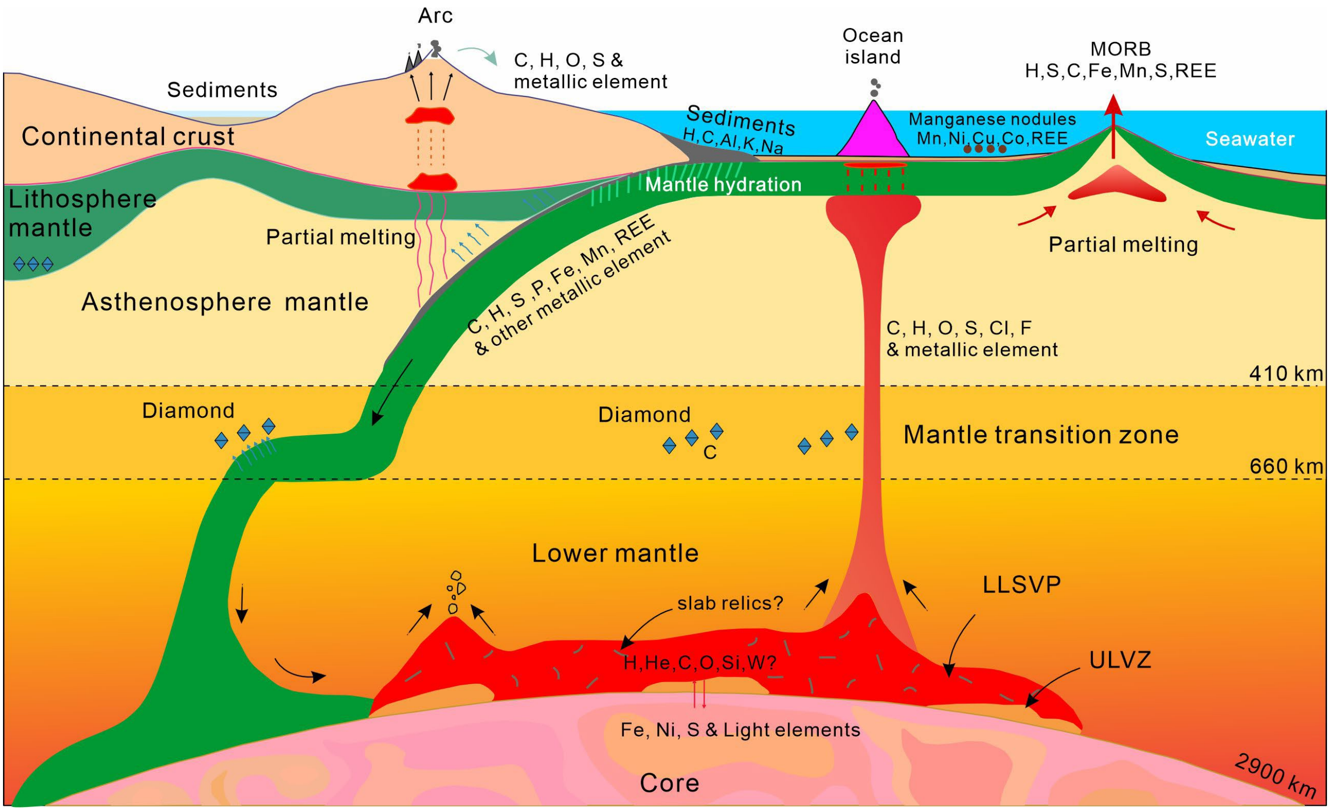

Figure 3. Recycling of elements in multi-sphere Earth system.

The Cambrian explosion of life, which evolved over three stages, marked a milestone in the evolution history of Earth habitability (Zhang and Shu 2014; Shu and Han 2020; Zhang *et al.* 2023; Yao *et al.* 2025; Song *et al.* 2026). This coincided with the supercontinent cycle transition from the breakup of the Rodinia supercontinent to the assembly of the Gondwana Landmasses (Figures 1, 4; Schmitt *et al.* 2018; Cawood 2020; Merdith *et al.* 2021; Yao *et al.* 2021b, 2025; Cui *et al.* 2026a), as well as possible establishment of modern plate tectonics (Cawood 2020; Stern *et al.* 2020; Yao *et al.* 2021a). Rapid geomagnetic reversals and the formation of Earth's inner core might have also occurred at this time (Meert *et al.* 2016; Bono *et al.* 2019; Zhou *et al.* 2022; Li *et al.* 2023). Meanwhile, surficial extreme events, including the Snowball Earth event and the Neoproterozoic Oxidation Event (NOE) occurred as well (Figure 1; Och and Shields-Zhou 2012; Lyons *et al.* 2014; Huang *et al.* 2016; Hoffman *et al.* 2017). These solid Earth and surficial events must have been internally linked, and this age period is thus the ideal window to research into Earth system science, along with how Earth evolved into a habitable planet. However, the links are mostly limited to conceptual models (Meert *et al.* 2016; Hoffman *et al.* 2017; Mills *et al.* 2017). We here review the changes of Earth system on a geological scale, and aim to uncover the triggers of Cambrian animal diversification from a solid Earth perspective.

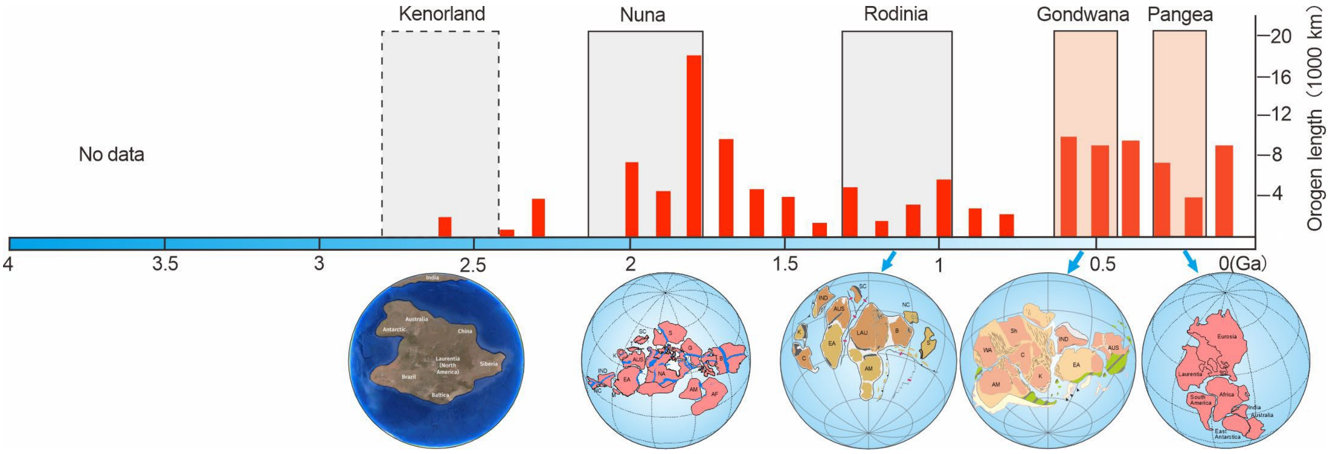

Figure 4. Supercontinents cycles in Earth history.

2. The evolution of Earth tectonic regime

2.1. Episodic evolution from stagnant lid to modern plate tectonics

Plate tectonics is one of the unique characteristics of Earth, but Earth was not born with Plate tectonics. Instead, the tectonic modes of Earth were developed as a result of secular mantle cooling, subsequent to the possible precursor lid tectonic modes (Figure 1; Sizova *et al.* 2010; Herzberg *et al.* 2010; Cawood *et al.* 2022). This is largely due to the fact that mantle temperature governs the strength of lithospheric slab, thereby controlling the evolution of the style of plate tectonics (Sizova *et al.* 2010, 2014; Gerya 2014). However, recent studies highlight that water-enriched sediments in subduction zone play an equally crucial role. Their presence in subduction channels can reduce the friction coefficient by up to one order of magnitude, significantly accelerating subduction rates (Soblev and Brown 2019). Higher subduction velocity not only stabilizes subduction and plate tectonic, but also preserves mantle heterogeneity, thereby sustaining the slab-pull force necessary to maintain a plate-tectonic regime.

There is a growing number of researches discussing what were the exact pre-Plate tectonics modes in Hadean to early Archean, and how were the tectonic modes evolved over time, along with when each tectonic modes occurred (Gerya *et al.* 2015; Yao *et al.* 2021a; Cawood *et al.* 2022; Zhao *et al.* 2025). Moreover, when and how plate tectonics initiated and evolved are even more hotly debated, but less well constrained (e.g., Hawkesworth *et al.* 2016; Stern 2020; Zheng and Zhao 2020; Bédard 2020; Palin *et al.* 2020), which largely varies from the Hadean to the Neoproterozoic time and will remain highly controversial (Palin *et al.* 2020). Nevertheless, a large group of researchers agree that the tectonic modes evolved from an initial magma ocean through crust–mantle differentiation that produced a soft or stagnant lid regime (the pre-plate tectonic stage) (Lenardic 2018; O'Neill and Zhang 2019; Bédard 2018; 2020), to early plate tectonics (hot subduction), Earth's middle age (sluggish subduction) and finally modern Plate tectonics (cold deep subduction) (Figure 1; Hawkesworth *et al.* 2016; Stern 2020; Zheng and Zhao 2020; Yao *et al.* 2021a). Notably, the recent proposal that each stage was characterized by dominant tectonic modes and sub-tectonic modes might better interpret known geological records and modellings results (Cawood *et al.* 2022).

In the middle to late Archean, as mantle temperatures cooled (ΔT < 250 °C relative to present-day values), slab strength increased, potentially enabling the onset of early plate tectonic (Figure 1; Sizova *et al.* 2010; Gerya *et al.* 2015; Cawood *et al.* 2022). Many researchers suggest that subduction and early plate tectonics, also referred to as "hot subduction," may have emerged during the Mesoarchean (ca. 3.6–3.0 Ga) (Gerya *et al.* 2015; Tang *et al.* 2016; Hawkesworth *et al.* 2016; Brown and Johnson 2018; Cawood 2020; Ge *et al.* 2023). However, due to the weak strength of the plates, deep subduction was not stable at this stage. Following the Paleoproterozoic Huronian glaciation, intense glacial erosion delivered vast quantities of sediment to subduction zones, allowing water-enriched sediments to facilitate the expansion of early plate tectonics to a global scale (Soblev and Brown, 2019). This further led to the occurrence of coeval high-pressure (HP) rocks reported from North China and Laurentia (Wan *et al.* 2015; Weller and St-Onge 2017). Some scholars preferred modern type plate tectonics at this time (Wan *et al.* 2015, 2020; Weller and St-Onge 2017), or earlier (Windley *et al.* 2021; Ning *et al.* 2022; Li *et al.* 2025; Huang *et al.* 2026). We believe that local deep subduction had already appeared at this time, but likely not on a global scale. Subsequently, Earth entered a middle-age phase of relatively subdued subduction, despite persistent non-subduction-related magmatism, thin crust, hot metamorphism, dry magmatism and REE metallogeny (Cawood and Hawkesworth 2014; Tang *et al.* 2021; Zhang *et al.* 2024; Yao *et al.* 2025; Jiao *et al.* 2026). The 'Earth's Middle age' coincides well with 'Boring Billion', with less active plate tectonics, surficial environs and life evolution (Holland 2006; Roberts 2013), although other researchers argue for pulsed environmental change (Zhang *et al.* 2021). In the middle to later Neoproterozoic, further cooling of the mantle ($\Delta T < 80$–100 °C) enhanced slab rigidity, likely triggering the onset of modern-style plate tectonics (Sizova *et al.* 2010; Stern 2020; Cawood, 2020). At this stage, slabs could have been subducted into the deep mantle. The super-orogens generated by super deep continental subduction, coupled with the termination of global glaciations, supplied enormous volumes of sediment to oceans and subduction zones (Soblev and Brown 2019), promoting the initiation and stabilization of the modern plate tectonic regime (Yao *et al.* 2021a, 2025).

2.2. The establishment of modern plate tectonics characterized by whole plate deep subduction

When the modern-style plate tectonic regime initiated on Earth is a key scientific question that has attracted wide international interest. Existing models largely vary from the Archean to the Cambrian (Stern 2013; Hawkesworth *et al.* 2016; Palin *et al.* 2020; Windley *et al.* 2021; Zheng and Zhao 2020; Yao *et al.* 2021a; Cawood *et al.* 2022; Ning *et al.* 2022). The variations among these models resulted from the varied definition of modern plate tectonics. There is no universally accepted definition for exactly what is modern plate tectonics, and also no practical proxies of how to define it. What are the distinctive features that distinguish modern plate tectonics from the earlier tectonic modes? More importantly, most geological studies have approached the evolution of Earth's tectonic regimes from a regional geology perspective, thus ignored the fact that plate tectonics represents a global mode on plate motions. Therefore, research on the evolution of tectonic styles must be reviewed from a global perspective, especially on issues such as when modern plate tectonics first emerged.

Particularly, the mantle temperature significantly cooled in the Neoproterozoic (Herzberg *et al.* 2010). This led to the global-scale deep subduction from a modelling perspective (Sizova *et al.* 2010, 2014), suggesting that the modern plate tectonic regime had finally been fully established on a global scale. On the other hand, the mantle temperature remained sufficiently high to sustain plastic flow in the mantle, which is a coupling condition that is essential for the operation of plate tectonics. The establishment of whole plate deep subduction is widely recorded by extensively developed high- and ultra-high-pressure metamorphic rocks (Holder *et al.* 2019; Brown *et al.* 2020), as well as the evolution trend of paired low-pressure (LP)/high-temperature (HT) and HP/low-temperature (LT) metamorphism, which reached precisely modern level in Ediacaran-Cambrian (Holder *et al.* 2019). This is consistent with the Cambrian ultra-high-pressure (UHP) stishovite (9 GPa) in the Altyn belt, indicating that continental subduction depths could have reached approximately 300 km (Liu *et al.* 2019). HP-UHP rocks widely occurred in orogens elsewhere at this age interval (Brown and Johnson 2018; Edgar *et al.* 2022), indicating widespread ultra-deep subduction. Deep subduction in turn led to significant cooling of the Earth, driving the temperature-to-pressure ratio (T/P) to new low levels (Figure 1; Brown *et al.* 2020). The whole plate deep continental subduction crust also coincides well with the coeval largest-scale continental crust recycling event in Earth's history recorded by Hf-O isotope evolution trends and recycling indicators (Cawood *et al.* 2022), as well as with the global scale tectonic re-organization (Yao *et al.* 2021a).

The deep continental subduction resulted in thickened continental crust since Gondwana assembly, and enabled formation of global-scale Himalayan-type continental collision orogens within its interior and accretionary orogens along its periphery (Figure 5). The new appearance of huge Gondwana orogens in the mid–low latitudes enhanced weathering of continental crust and supplied extensive sediments to the oceans. The sediments further improved subduction velocity and sustained plate tectonics. This is well recorded by the fast plate motion and true polar wander in Gondwana cycle (Evans 2003; Mitchell *et al.* 2010; Bradley 2011). Therefore, the establishment of modern plate tectonics initiated endogenic and positive response that further enhanced plate tectonics.

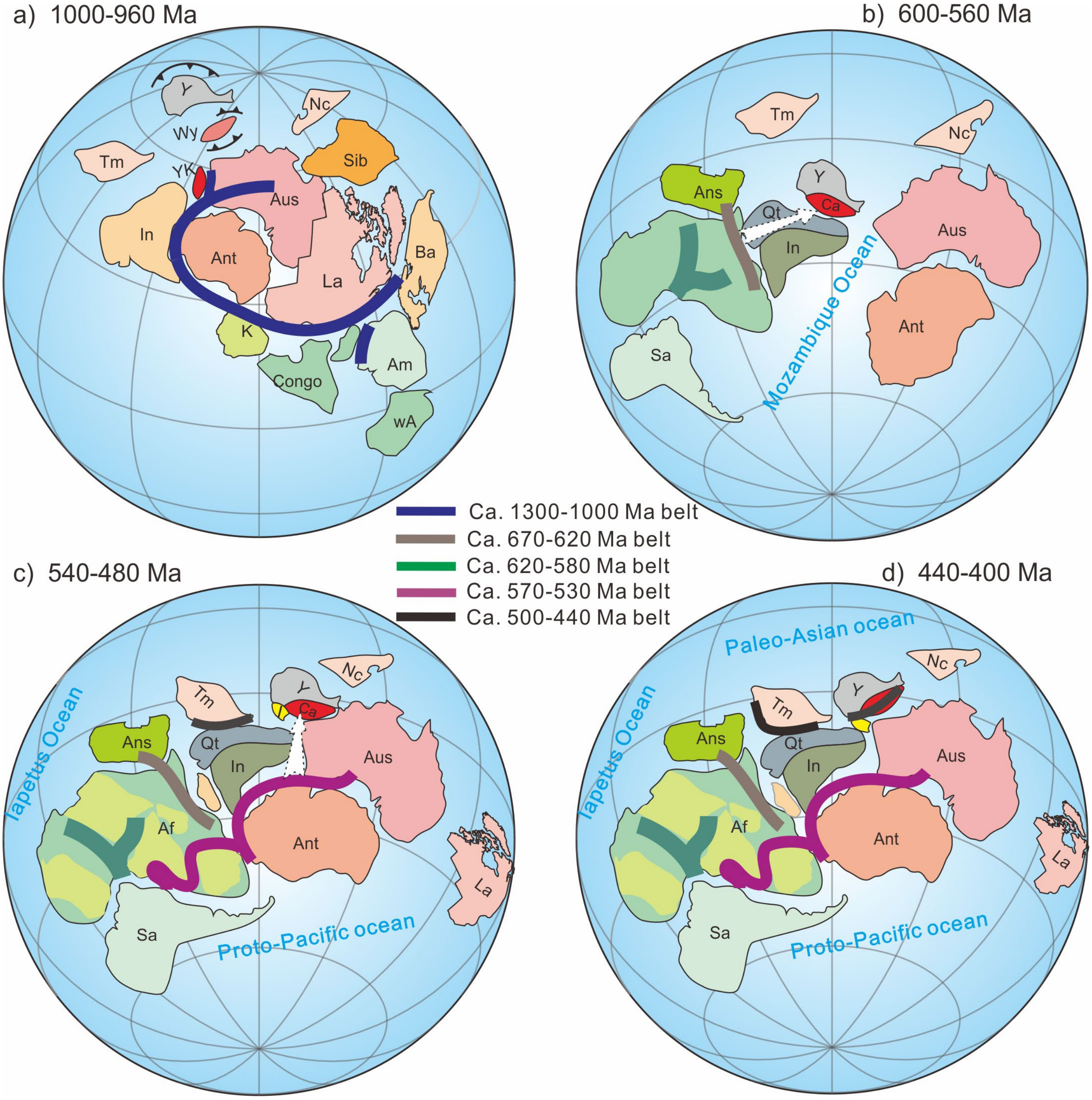

Figure 5. Supercontinent reconstruction of Rodinia and Gondwana and distribution of orogens (Revised after Yao *et al.* 2025).

Overall, the lithospheric evolution indicators show that during the Gondwana assembly stage, a milestone transition of tectonics occurred. It was during this period that Earth's tectonic regime finally reached an absolute modern plate-tectonic system. Although there is still no universally accepted consensus on the definition of how to distinguish modern plate-tectonics, this study argues that the modern plate-tectonic system was established during the Gondwana assembly. We agree that regional modern plate tectonics initiated in later Archean or Paleoproterozoic, but have not reached global level at these times and was only a subordinate tectonic mode at that time. Furthermore, regarding how to distinguish modern and early plate tectonics, we suggest whole plate deep subduction and global scale tectonic reorganization.

3. The supercontinent cycle in the Neoproterozoic to early Paleozoic

Since the initiation of plate tectonics, supercontinents have been episodically formed throughout Earth's history. In times of nearly all continental blocks assembled, a supercontinent was formed. Current geological evidence indicates that several supercontinents or mega-continents have been formed, including, Nuna (also called Columbia, ~1.9–1.8 Ga), Rodinia (~1.0–0.8 Ga), Gondwana (~0.68–0.43 Ga), and Pangea (~0.25 Ga) (Figure 4; Zhao *et al.* 2002, 2018; Gray *et al.* 2008; Evans 2013; Spencer *et al.* 2013; Cawood and Pisarevsky 2017).

Nuna is widely accepted as Earth's first supercontinent, with its assembly at ~2.0–1.7 Ga through global-scale collisional orogenesis (Zhao *et al.* 2002). Paleomagnetic and geologic evidence indicates that Nuna remained as a remarkably stable, continental "lid" for an extended period, lasting until at least ~1.3 Ga. During this time, plate tectonics continued along its periphery as accretionary orogens, leading to continued growth of continental crust (Condie 2013). The Nuna supercontinent might have not totally broke up and continued to the Rodinia time (Cawood and Hawkesworth 2014), the transition thus involved the transformation of external accretionary orogens into internal collisional orogen. The Neoproterozoic to early Paleozoic age period recoded the Supercontinent cycle from Rodinia breakup to Gondwana assembly (Figure 5), which are two trans-timing events and overlapped with each other. This period also witnessed three major Neoproterozoic glaciations (Sturtian, Marinoan, Gaskiers) (Hoffman *et al.* 2017). The initial breakup of the Rodinia supercontinent occurred at approximately 850 Ma (Li *et al.* 2008), primarily in the interior of Rodinia, whereas large-scale rift magmatic activity was mainly concentrated between 825 Ma and 740 Ma (Li *et al.* 2008). The finial breakup continued to 650–600 Ma, which separated the Amazonian Craton and the southeastern margin of Laurentia (Li *et al.* 2008; Cawood *et al.* 2016). The stepwise amalgamation of Gondwana occurred at ~670–440 Ma, with expansion of continental arcs and subsequent mountain building that generated over 9000 km orogenic belts (Figures 4 and 5). The Gondwana landmasses was formed by multi-stage orogens. The collision between East and West Gondwana, including India, Madagascar, and Sri Lanka with East Africa, generated the East African Orogen (~670–650 Ma). The subsequent Brasiliano-Damara Orogen (600–530 Ma) led to the amalgamation of the South America and Africa blocks (Figure 5). The third stage orogens include that the Kuunga Orogen (530–520 Ma) that amalgamated Australia and Antarctica with Gondwana, completing the basic framework of the Gondwana landmasses (Meert and Van 1997; Gray *et al.* 2008; Schmitt *et al.* 2018). The East Asian blocks, including South China, Alxa, Qaidam, and Tarim blocks, were accreted to the northern Gondwana during the Cambrian–Ordovician period (500–430 Ma) (Cawood *et al.* 2016; Zhao *et al.* 2018; Yao *et al.* 2021b; Yang *et al.* 2025; Chen *et al.* 2026), but their precise paleogeographic positions are still hotly debated. In addition, weather the North China block was a member of Gondwana is less constrained (Dong and Santosh 2016; Zhao *et al.* 2020). Consequently, the East African, Kuunga, Brasiliano-Damara, and East Asian orogenic belts constituted the principal four stage orogenic systems for the assembly of Gondwana (Meert and Lieberman 2008; Yao *et al.* 2021b). These orogens were up to 9000 km long and were located in low-to-mid latitudes (Figure 5).

4. Coupled evolution of Precambrian tectonics and Earth surface environs

Most earlier Earth system models focus on the Phanerozoic period (Nance *et al.* 2014; Zhao *et al.* 2022), while the Precambrian internal links between geological processes and surficial environs are less constrained. However, the widely developed early Precambrian vertical tectonic processes, including "heat-pipe" tectonics and mantle plumes (Gerya *et al.* 2015; Cawood *et al.* 2022), along with Proterozoic early Plate tectonics and Earth's middle age (Cawood and Hawkesworth 2014), must have made critical contributions to the evolution of Earth's habitability. For example, Earth continental crust was formed at this period (Zhao and Zhang 2021; Ge *et al.* 2023; Zhao *et al.* 2025), either by the initiation of plate tectonics during (Ge *et al.* 2023), or by plumes (Van Kranendonk *et al.* 2007).

The subsequent formation, stability, and breakup of the Columbia (Nuna) and Rodinia supercontinents marked stepwise contribution to evolution of surface environment and life, offering insights to decipher how deep Earth geodynamics and surface environmental systems are internally coupled. The assembly of Nuna was followed by the 'Earth's middle age' and 'Boring Billion' at 1.8–0.8 Ga. This represents a special period in the history of Earth's tectonic regime evolution, characterized by sluggish plate activity, widespread ultra-high-temperature (UHT) metamorphism, and the development of anhydrous magmatic rocks such as A-type granites and anorthosites, along with continental crust thinning (Cawood and Hawkesworth 2014; Tang *et al.* 2021). The unique tectonics also formed large extensional-type deposits (Jiao *et al.* 2026). During this interval, oxygenation occurred, but atmospheric oxygen levels remained low, while carbon isotopes showed no significant variation (Holland *et al.* 2006; Lyons *et al.* 2021; Zhang *et al.* 2021). At around 1.3 Ga, environs recorded pulsed change (Zhang *et al.* 2021), which temporally matches the breakup of Nuna (Zhang *et al.* 2009). This indicates that the less active tectonics caused a long-term quiescence and stasis in the surface environmental system. No extreme environmental change occurred during the assembly Rodinia, but the breakup of Rodinia had profound and dramatic environmental consequences. The initial breakup of Rodinia led to CO_2 degassing, whereas weathering of subsequent continental flood basalt consumed atmosphere CO_2 (Cox *et al.* 2016). In addition, increased new continental margins dramatically increasing the global capacity for organic carbon burial. Thus, combined effect led to a drawdown of atmospheric CO_2, tipping a series of catastrophic ice-albedo feedbacks that formed the Neoproterozoic Snowball Earth events

(Hoffman *et al.* 2017). The extreme environmental factors, imposed selection pressures that stimulated the subsequent radiation of complex life, including the Ediacaran biota and the Cambrian Explosion.

5. Extreme Earth magnetic field linked to possible formation of Earth inner core and modern plate tectonics

The Earth's geomagnetic field intensity reached its lowest level during the Ediacaran–Cambrian period (0.7×10^{22} Am²as compared to present 8×10^{22} Am²) (Figure 1; Bono *et al.* 2019; Zhou *et al.* 2022), and was highly unstable and characterized by exceptionally frequent reversals (Li *et al.* 2023; Shen *et al.* 2025). Simultaneously, this milestone age period was also marked by the super high frequent geomagnetic polarity reversals of 20–25 times per million years (Shen *et al.* 2025), seven times higher than normal Earth's magnetic field reversals of about 2–3 times per million years. This indicates the collapse of the Earth geodynamo mechanism that drives the magnetic field (Driscoll 2016). The extreme state of the global magnetic field anomaly might have been directly linked to the initial formation of the solid inner core (Bono *et al.* 2019; Zhou *et al.* 2022), but is still less constrained. Earth's magnetic field is primarily generated by the convection of liquid iron in the outer core. The growth of the solid inner core would have released substantial heat and light elements, providing new additional energy for outer core convection. This might have led to the ultra-low magnetic field strength and high reversal frequency during the Ediacaran (Bono *et al.* 2019). Therefore, the magnetic extreme event should have recorded a major transformation occurring in Earth's most central part. Given that the initial formation of the solid inner core coincided well with the establishment of modern plate tectonics, we here further propose that the formation of Earth inner core might have been caused by the cooling of the Earth's interior due to whole plate deep subduction under the modern plate tectonic regime.

6. Conceptual models of multi-sphere driving mechanism linked to the Cambrian explosion of life

The Ediacaran–Early Cambrian explosion of life led to the first appearance of animals on Earth, which occurred through three stage evolution and is a milestone in the history of biological evolution (Zhang and Shu 2014; Shu *et al.* 2020; Zhang *et al.* 2023). The event laid the foundational framework for modern animal systems, as all phylum of animals occurred on Earth since this time (Knoll and Nowak 2017; Shu *et al.* 2020; Wood *et al.* 2019). This established the marine ecosystems for the first time, which was driven by animal dominance and consumption, giving rise to a complete food chain composed of producers (bacteria and algae), consumers (early animals), and decomposers (microorganisms) (Zhang *et al.* 2021). The Cambrian explosion overlap well with the tectonic and environmental changes during the Neoproterozoic–Cambrian time, especially the rise of atmospheric oxygen levels (NOE) (Lyons *et al.* 2014), the Snowball Earth events (Hoffman *et al.* 2017), the establish of modern plate tectonics and Gondwana assembly (Yao *et al.* 2021a), as well as the Extreme Earth geomagnetic field discussed above. The coupling of these events given rise to fundamental scientific issues such as, when was the modern Earth system assembled? What are the coupling mechanisms between the lithosphere and surficial spheres?

Geological scale Earth system models are mostly limited to conceptual models. Many scholars believe that in the Neoproterozoic-Cambrian periods, tectonic coupled with changes in the Earth's magnetic field, served as the primary driving force for environmental changes and the Cambrian life Explosion (Campbell and Allen 2008; Li *et al.* 2013; Cox *et al.* 2016; Hoffman *et al.* 2017; Williams *et al.* 2019; Yao *et al.* 2021a). These events profoundly reshaped global marine ecosystems, significantly improved the supply of marine nutrients and the global carbon cycle, thereby leading to a marked increase in both atmospheric and oceanic oxidation levels as well as surface temperatures (Campbell and Squire 2010; Mills *et al.* 2017; Dodd *et al.* 2023, 2025). This provided the environmental, material, and ecological space necessary for the survival of marine animals. However, the precise mechanisms governing the coupling among Earth's various spheres during this period remain inconclusive, as are the key tectonic factors promoting the evolution of marine ecosystems.

Conceptual models for Earth system in the late Neoproterozoic to Cambrian period include 'super orogen driven by plate tectonics', 'mantle plume activity associated with Rodinia breakup', 'tectonic degassing' and 'low geomagnetic field intensity and high frequent reversals' (Campbell and Allen 2008; Li *et al.* 2013; Cawood *et al.* 2016; Meert *et al.* 2016; Hoffman *et al.* 2017; Yao *et al.* 2021b; Huang *et al.* 2024). The mantle plume model posits that mantle plume activity related to the breakup of Rodinia triggered massive P and Fe elements enriched continental flood basalts, which were eventually by transported into the oceans and enhanced marine primary productivity and triggered atmospheric and oceanic oxygenation (Santosh *et al.* 2014; Horton 2015; Cox *et al.* 2016; Gernon *et al.* 2016). On the other hand, the rapid weathering of these basic rocks significantly consumed atmospheric CO_2 and triggered the Neoproterozoic Snowball Earth events (Kennedy *et al.* 2001; Cox *et al.* 2016; Hoffman *et al.* 2017). It is noteworthy that mantle plume magmatism was widespread in the Cryogenian (850–750 Ma), but remarkably limited during the latest Cryogenian to Cambrian periods (Li *et al.* 2013; Ernst *et al.* 2021). In contrast, the orogenic-driven model suggests that the establishment of modern plate tectonics and amalgamation of the Gondwana landmasses led to the emergence of unprecedentedly large-scale orogenic belts (Campbell and Squire 2010; Yao *et al.* 2021a). These long-term, low-latitude orogenic belts could have induced massive continental weathering and erosion, delivering substantial nutrient elements into the oceans, which altered ocean chemistry and boosted marine productivity, thus promoting atmospheric oxygenation and providing a key threshold for biological radiation (Campbell and Squire 2010; Shields *et al.* 2019; Yao *et al.* 2021a). Furthermore, in recent years, some scholars have proposed that the scale of arc magmatism in subduction zones increased during the late Neoproterozoic, resulting in sustained and widespread accretion along continental margins (Li *et al.* 2013; Cawood *et al.* 2016), which in turn elevated the rates of arc magmatic degassing and CO_2 emissions (Mills *et al.* 2017). The enhanced supply of photosynthetic precursors would have been sufficient to trigger the Neoproterozoic atmospheric oxygenation (Williams *et al.* 2019).

The model that extreme geomagnetic field triggered surficial change in the E-C eras is also popular (Meert *et al.* 2016; Huang *et al.* 2024), although some research disagrees (Lingam 2019). The geomagnetic field deflects the solar wind and high-energy cosmic rays. A sudden drop to one-tenth of its current intensity in E-C boundary would have led to the decrease of the magnetopause (the boundary of the magnetic field) from its current distance of about 10 Earth radii to 4–5 Earth radii. The weakening of the magnetic shield could have resulted in more high-energy particles penetrating the atmosphere, potentially causing damage to life on Earth (Meert *et al.* 2016). On the other hand, solar wind particles would have acted more directly with the upper atmosphere, potentially leading to ozone depletion and oxygen escape. This should have led to the Late Ediacaran Extinction, when the soft-bodied and stationary Ediacaran biota may have been the first to suffer in an environment with sharply increased UV-B radiation, ultimately leading to their extinction (Levashova *et al.* 2021). The crisis may have pressed the “accelerator” for animal evolution. Stronger UV radiation became a powerful selective pressure. Organisms capable of digging vertical burrows to avoid radiation, evolving biomineralized shells as protective shields, or moving freely in water to evade harm gained significant survival advantages. These environmental changes may have triggered the Cambrian Explosion (Meert *et al.* 2016; Huang *et al.* 2024). This chronological sequence leads many scientists to believe that the dramatic environmental changes disrupted the balance of precursor ecosystems, creating ecological space for the rise of new life. On the other hand, the geomagnetic polarity reversals would have meant surface life experienced dramatic flips between the magnetic north and south poles every few tens of thousands of years, exert extreme environmental stress on evolution of life.

The debate surrounding these models lies in the lack of long-term quantitative characterization of both tectonic and magmatic processes, which has constrained our ability to compare solid-Earth processes with surface processes and to explore their coupling mechanisms. Based on a review of all events, we believed that the Earth system was driven by multiple factors. The mantle plumes may have served as the initiating trigger, while orogens and subduction zones under the modern plate-tectonic regime during the Gondwana amalgamation, coupled with extreme geomagnetic field, acted as a sustained driving force over geological timescales. In other words, the Cambrian life Explosion and NOE were the products of coupled multiple geological processes, as well as results of low possibility coincidence.

7. Tectonic drivers of oxygenation and the carbon cycle

As one of Earth’s “unique characteristics”, since its establishment at around 3.6–3.0 Ga (Tang *et al.* 2016; Ge *et al.* 2023), plate tectonics drives the exchange and cycling of materials and energy between different Earth spheres, thus acting as a first-order driving force and a key “engine” for the evolution of Earth’s habitability (Figure 3; Elkins-Tanton 2013; Shahar 2019; Xu *et al.* 2024). The deep-time and deep Earth cycles of key elements on Earth, such as carbon, hydrogen, oxygen, and sulfur, are all regulated by plate tectonic processes (Figure 6; Dasgupta 2013; Schmitt *et al.* 2018; Wang *et al.* 2018; Bufe *et al.* 2024; Li *et al.* 2025). Through mountain building, basin formation, water cycling, and climate regulation, plate tectonics has provided the continental foundation for human survival on the surface, formed ocean basins as reservoirs for surface water, and laid the foundation for the persistence of life (Figure 6; Arndt 2013; Zhao and Zhang 2021; Xu and Xie 2024; Chowdhury *et al.* 2025; Ding *et al.* 2026), ultimately driving Earth to have evolved into a relatively stable, self-regulating and self-repairing habitable planet (Xu *et al.* 2024). On the other, plume tectonics, as an endmember model of vertical tectonics, also likely contributed to formation of continental crust and triggered initiation of plate tectonics (Gerya *et al.* 2015; Zhao *et al.* 2025). Plumes also drives recycling of elements from deep Solid Earth into surficial sphere, trigger environmental change and life extinction events (Figure 6; Bralower *et al.* 2008; Neal *et al.* 2008; Bond and Wignall 2014; Cox *et al.* 2016; Gernon *et al.* 2016; Horton 2015; Brune *et al.* 2017; Hoffman *et al.* 2017). Therefore, plate and plume tectonic processes and the sphere-scale material cycles represent a key breakthrough in exploring the scientific connotation of the evolution of Earth’s habitability.

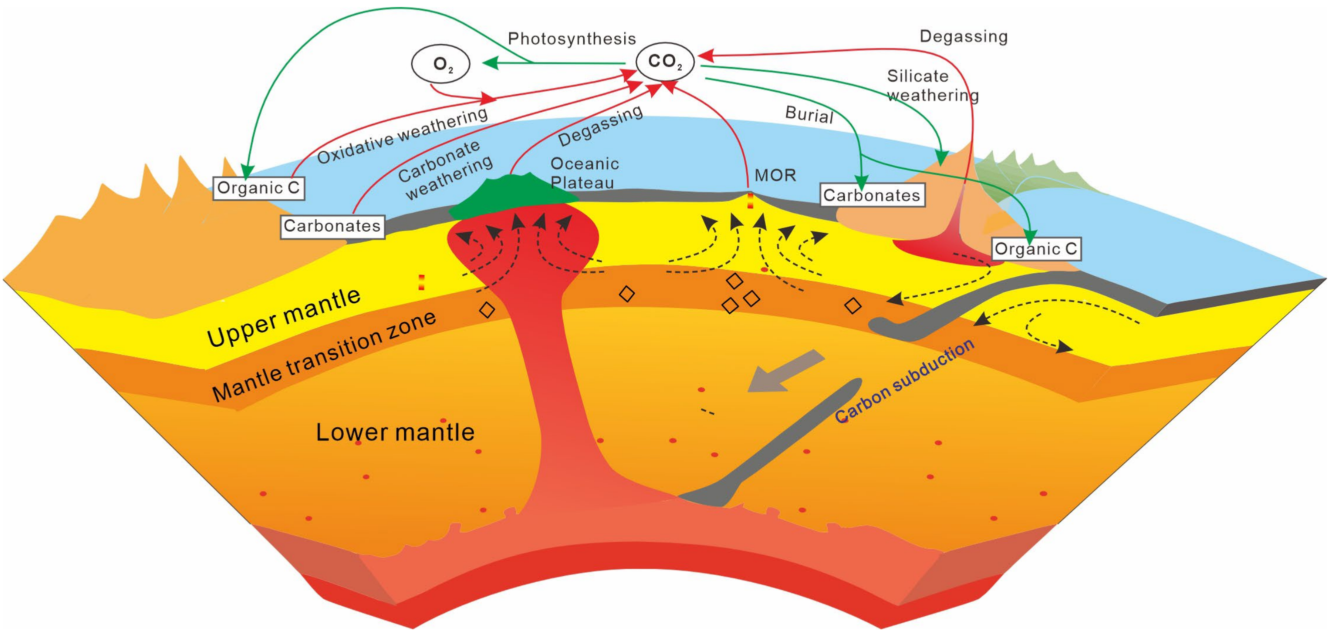

Figure 6. Model representations of the carbon and oxygen cycles with respect to the atmosphere reservoir.

7.1. Large-scale weathering and erosion during Gondwana assembly sustained the Neoproterozoic Oxidation Event

The topography of Earth drives the circulation of elements among varied surficial reservoirs, and is thus as a key factor that links tectonics and biochemicals (Figure 7). It is also a critical component of atmospheric and hydrological cycles and is linked to solid Earth processes through geological mechanisms such as subduction, collision, orogeny, weathering, and erosion (Liu *et al.* 2018; Tang *et al.* 2021, 2024; Xu *et al.* 2024; Ding *et al.* 2026). Consequently, topography links terrestrial and marine ecosystems. Earth topography, the distribution of continents, mountains and oceans, occurred as results of tectonic processes and bimodal distribution of the density of continental and oceanic crust. The theory of isostasy indicates that the higher a mountain, the deeper its root (Airy 1855; Pratt 1855; Bowie 1926; Gratton 1989), due to the fact that the crust is less dense than the underlying mantle. Thus, the continental crustal root provides buoyancy for the mountains, meaning that the greater the crustal thickness, the higher the surface elevation. The extensive exposure of modern continents above sea level is attributed to the fact that continental crust is significantly thicker and less dense than the oceanic crust. The core scientific question how the topography evolved in Earth history and when modern-style topography emerged on Earth.

Given the less continental crust volume and more easily eclogitized lower continental crust, along with thicker oceanic crust, the Hadean and early Archean Earth was a watery planet (Figure 7; Zhai *et al.* 2022; Tang *et al.* 2024; Chowdhury *et al.* 2025). This resulted in less emerged continental crust, leading to low weathering rates. This limited the transport of nutrients, particularly P and Fe, from the continents to the oceans. Furthermore, with primary producers being simple prokaryotes with low oxygen production efficiency, while the rate of oxygen production via photosynthesis was lower than the consumption by reducing volcanic gases, resulting in low atmospheric oxygen levels (Höning and Spohn 2016; Korenaga 2018). Anyway, the progressive emergence of continents since Mesoarchean significantly altered the photochemical processes and the cycling of bio-essential nutrients (Hao *et al.* 2025), but the phosphorus bioavailability was still limited by phyllosilicate adsorption in early ferruginous oceans (Cui *et al.* 2026b). With continental growth and uplift, coupled with the differentiation of the continental and oceanic crust, orogenic weathering and erosion significantly intensified.

During the Nuna and Gondwana assembly stage, the formation of long-duration, multi-stage, global super-orogenic belts occurred. In the Gondwana stage, most of these mountain ranges were situated in the low-to-mid latitude monsoon belts (Figure 5), where weathering was intense, leading to a further increase in chemical weathering rates. Consequently, continental weathering and erosion were significantly enhanced during this period (Shields-Zhou and Och 2011). This enhanced chemical weathering resulted in a dramatic increase in the flux of nutrients transported to the oceans. This is entirely consistent with the significant rise in the Neoproterozoic–Early Paleozoic seawater $^{87}Sr/^{86}Sr$ ratio, which reached its highest value in Earth's history during this interval (Shields 2007; Chen *et al.* 2022). Weathering and erosion serve as a critical link connecting tectonic processes with environmental and biological evolution, playing a pivotal role in Earth's history. Recent quantitative sediment flux models show a positive correlation between sediment flux and marine animal diversity (Salles *et al.* 2023). More importantly, the NOE event is closely related to ocean productivity driven by continental supply of nutritious elements (Santosh *et al.* 2014; Horton 2015; Cox *et al.* 2016; Yao *et al.* 2021a; Cui *et al.* 2026b), triggered by mantle plume and super-orogens.

Overall, subsequent to the Rodinia breakup mantle plume, the massive orogeny and the differentiation of continental and oceanic topography during the Gondwana assembly led to the transport of vast quantities of continental weathering products (terrestrial sediments) into the ocean eco system. This further drove changes in ocean composition and enhanced marine productivity, while simultaneously intensifying organic matter burial and the oxidation of the Earth's surface environment, thereby providing the material foundation for the great radiation of animal phyla.

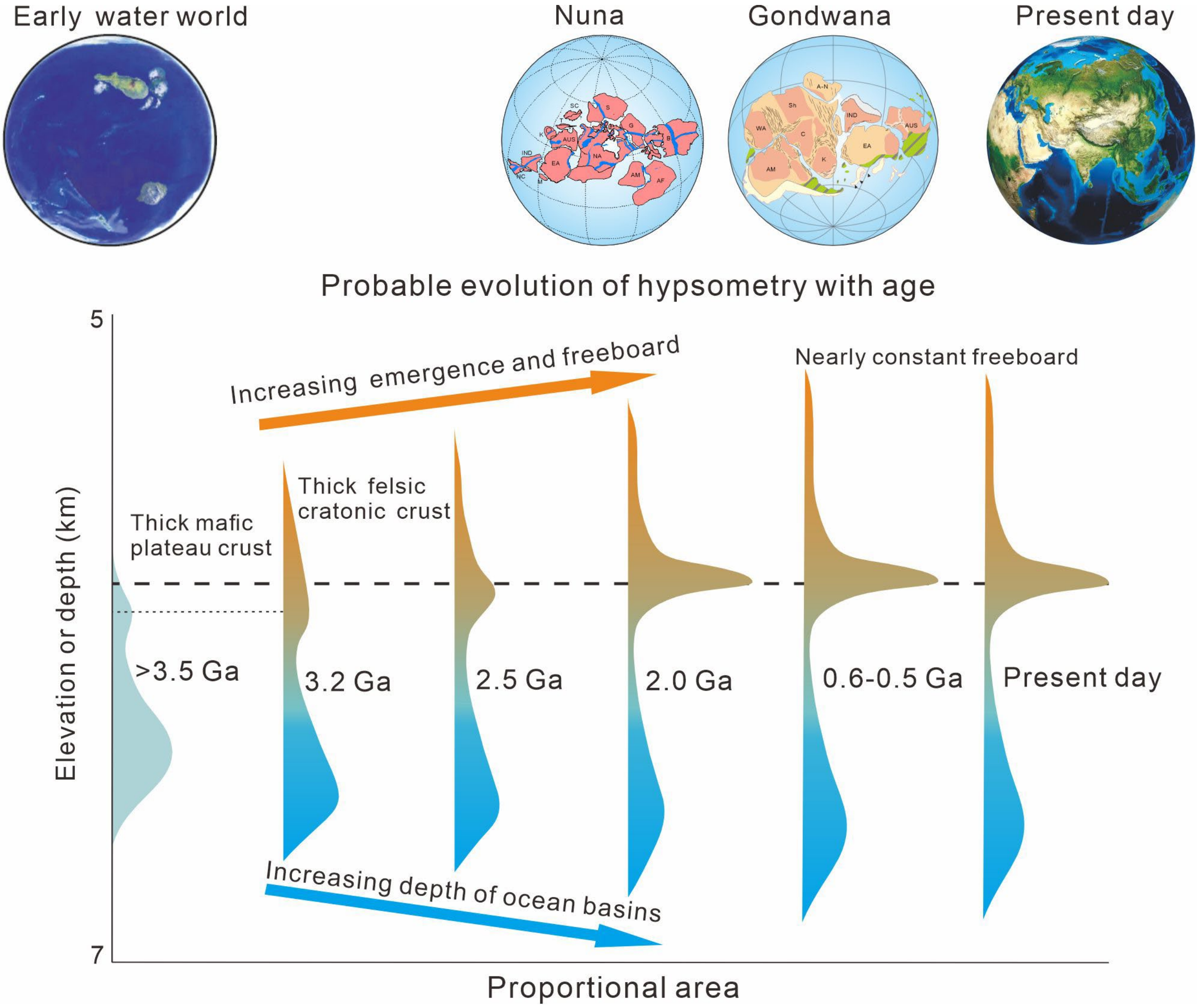

Figure 7. Possible evolution of Earth's hypsometry along with schematic curves (revised after Chowdhury *et al.* 2025).

7.2. Tectonics drove the Neoproterozoic—Cambrian carbon cycle

Atmospheric CO_2 has played a key role in maintaining a habitable planetary environment (Langmuir and Broecker 2012; Elkins-Tanton 2013; Xu *et al.* 2024). CO_2 not only regulate planetary surface temperature and continental erosion rate (Walker *et al.* 1981; Isson *et al.* 2020), but also provides the necessary materials for photosynthesis. On a geological scale, the carbon cycle of Earth is largely controlled by tectonics, including plate tectonics and plume tectonics (Figure 1; Zhu *et al.* 2025; Xu *et al.* 2024). The long-term (> 10^5 yr) carbon inputs to the atmosphere carbon reservoir include direct mantle degassing, tectonic recycling and devolatilization of carbon-bearing sediments and subaerial weathering of carbonate rocks or fossil organic carbon (Williams *et al.* 2019; Isson *et al.* 2020). The geological scale carbon sinks from the atmosphere carbon reservoir are organic carbon burial and marine carbonate deposition, along with continental silicate weathering and hydrothermal alteration of the ocean floor (seafloor weathering) (Mills *et al.* 2017). Despite the complexity of the carbon cycle and its various models, the regulation of atmospheric CO_2 concentration is generally considered to depend on the balance between the total CO_2 degassing rate and the continental silicate weathering rates (Berner 1997).

7.2.1. Carbon cycling driven by Rodinia mantle plume

Particularly, the rifting of the Rodinia supercontinent was accompanied by Large Igneous Province (LIP) eruptions and CO_2 degassing, primarily between 820–700 Ma. Since basalt weathers faster than the average upper crust, the LIPs led to massive consumption of atmospheric CO_2, which not only caused a decline in CO_2 concentrations and triggered the Snowball Earth events, but also increased the input of phosphorus into the oceans and boosted primary productivity (Cox *et al.* 2016; Gernon *et al.* 2016; Hoffman *et al.* 2017; Zerkle 2018; Lyons *et al.* 2021), initiating atmospheric oxygenation. The weathering of these LIPs peaked in the mid-Neoproterozoic and declined rapidly thereafter, a trend that aligns highly with changes in Neoproterozoic seawater carbon isotope ratios and the timing of Snowball Earth events, proving that LIP weathering was a carbon sink and triggering factor for the pulsed 'Snowball Earth' events (Kirschvink 1992; Fairchild and Kennedy 2007; Cox *et al.* 2016; Gernon *et al.* 2016; Hoffman *et al.* 1998, 2017). The ending of the 'Snowball Earth' might have been related to LIPs degassing, and led to abrupt sediments supply to the oceans, acting as initial trigger of biogeochemical changes in the ocean system and Neoproterozoic oxygenation events (Canfield *et al.* 2007; Shields-Zhou and Och 2011; Och and Shields-Zhou 2012; Sahoo *et al.* 2012; Lyons *et al.* 2014).

7.2.2. Carbon cycling driven by subduction–accretion orogenesis during Gondwana assembly

The scale of global subduction zone was exceptionally high in Ediacaran-Cambrian (Hawkesworth *et al.* 2016; Palin *et al.* 2020; Stern 2020; Zheng and Zhao 2020; Cawood *et al.* 2022), which subducted huge oceanic crustal materials and carbonate-rich sediments into deep Earth. These subducted carbonate rocks were then subjected to metamorphic decarbonation reactions at sub-arc depths (e.g., $CaCO_3 + SiO_2 \rightarrow CaSiO_3 + CO_2$), thereby releasing enormous amounts of CO_2 to the atmosphere via arc volcanism degassing (Williams *et al.* 2019). Modelled results indicate coupled CO_2 levels with scales of subduction zones (Mills *et al.* 2017). Consequently, the Gondwana large-scale subduction zone functioned as an unprecedentedly powerful carbon source that continuously degassed CO_2 into the atmosphere–ocean system and maintained elevated atmospheric CO_2 partial pressure (pCO_2) during this interval (Figure 8).

During Gondwana assembly, arc magmatic activity along subduction zones continuously degassed CO_2, preventing Earth from descending into a permanent "icehouse" state due to excessive weathering and maintained surface temperatures above the critical threshold for life survival (Figure 8; Li *et al.* 2025). On the other hand, intense silicate weathering persistently consumed CO_2, exerting a negative feedback cooling effect and moderating global temperatures from reaching excessively high levels. Concurrently, weathering processes delivered large quantities of nutrients (e.g., phosphorus) into the oceans, promoting primary productivity and organic carbon burial, which constituted a key mechanism driving the atmospheric–oceanic oxygenation (Neoproterozoic Oxygenation Event, NOE) (Walker *et al.* 1981; Och and Shields-Zhou 2012). This negative feedback mechanism was established on a global and high-intensity scale during the Gondwanan period, providing Earth with long-term climatic stability (Mills *et al.* 2017; Li *et al.* 2025). This coincides well with the fact that the marine carbonate rocks recorded a pronounced $\delta^{13}C$ decrease to minimal values during the Gondwana assembly, while atmospheric O_2 concentrations increased during this stage (Lyons *et al.* 2014). This carbon-cycle mode created a surficial environment characterized by "continuously increasing oxygenation, sufficient nutrients, and relatively stable climate" (Krissansen-Totton *et al.* 2018). This precisely satisfied the requirements of the large-scale radiation of complex multicellular animals (metazoans) in terms of energy supply (aerobic metabolism), biomineralization (calcium carbonate skeleton formation requiring suitable marine carbonate chemistry), and ecosystem stability (necessitating a prolonged stable climatic window) (Sperling *et al.* 2013). Therefore, the carbon-cycle transition driven by Gondwana Subduction–Accretion Orogenesis was not only a turning point in the chemical environment of Earth's surface but also provided an indispensable, warm, and oxygen-rich "incubator" that paved the way for the subsequent Cambrian Explosion of life (Figure 8; Wu *et al.* 2025; Yao *et al.* 2025).

In summary, Earth's environmental changes from the Neoproterozoic to the Early Cambrian were a coupled process likely involving the interaction of multiple geological mechanisms. These include magmatic-metamorphic activity in continental arcs, mantle plume activity, LIP eruptions, and long-term sustained subduction-accretion and collisional orogen. These processes drove the evolution of Earth's atmosphere, oceans, and biosphere.

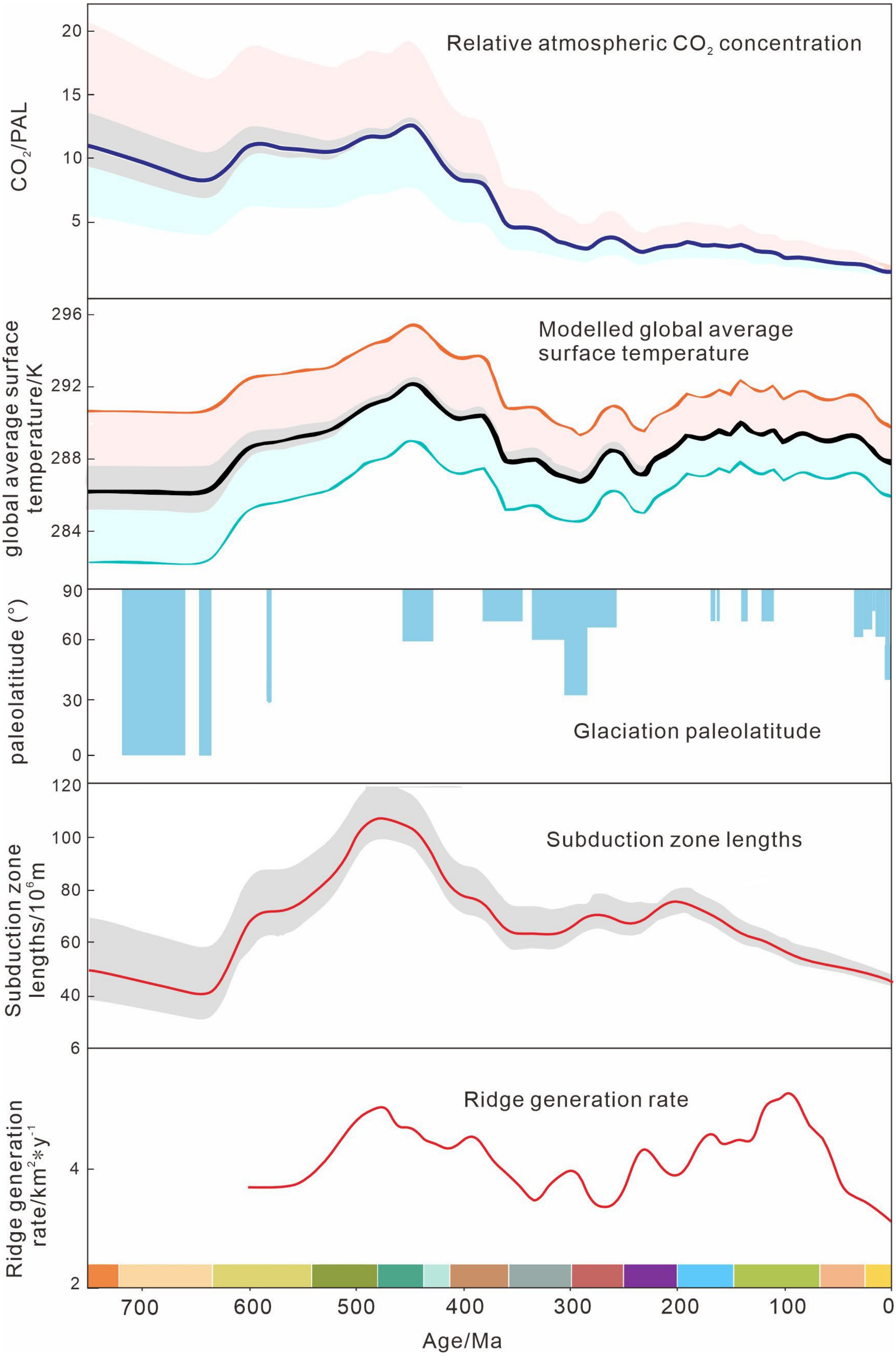

Figure 8. Evolution of global atmospheric carbon recycling and lengths of subduction zones (revised after Mills *et al.* 2017).

8. Coupled tectonic-environmental changes and geomagnetic field may have triggered the Ediacaran radiation and the Cambrian explosion

Over a span of approximately 42 million years, from 560 to 518 million years ago, the Cambrian Explosion occurred, during which all animal phyla appeared (Zhang and Shu 2014; Shu and Han 2020; Zhang *et al.* 2023), which is the most spectacular event of biological innovation in Earth history. The Cambrian Explosion stands as the only event in Earth's history involving the genesis of animal phyla, resulting in the near-simultaneous appearance of almost all modern animal phyla in the Early Cambrian oceans (Zhang *et al.* 2023). This event marked the formation of the animal tree of life, a stage during which organisms underwent three phases of episodic evolution (Shu and Han 2020). No new animal phyla emerged during other major geological events, including the colonization of land by plants and animals. Understanding why almost all animal phyla appeared in a burst over a short period, coinciding with massive changes across multiple Earth spheres, remains one of the most challenging questions in Earth science and evolutionary biology (Grey *et al.* 2003; Squire *et al.* 2006; Canfield *et al.* 2007; Campbell and Allen 2008; Zhang and Shu 2014, 2021; Liu *et al.* 2024; Pruss and Gill 2024; Wu *et al.* 2025).

The animals thrived during Ediacaran-Cambrian are successors of the survivors of complex life forms of the Snowball Earth events (Hoffman *et al.* 2017; Hoffman 2025), which should have occurred at least in the Tonian-Cryogenian Period (Yuan *et al.* 2023). The plume triggered Snowball Earth events may have contributed greatly to Cambrian explosion and is thus the dawn of the rising of animals. Snowball Earth blocked sunlight, leading to a cascading decline in photosynthesis and a depletion of marine nutrients (Kirschvink 1992; Hoffman *et al.* 1998, 2017). Meanwhile, recycling between the ocean and atmosphere was severely limited, resulting in widespread ocean anoxia and even euxinic (sulfidic) conditions (Shen *et al.* 2022). This posed a challenge to early life that depended on oxygen and photosynthesis. The survival pressure may have acted as a powerful "selective" force (Planavsky *et al.* 2010). In the nutrition limited subglacial ocean, larger multicellular organisms probably possessed a survival advantage over single-celled organisms, thereby driving the critical evolutionary transition from unicellular eukaryotes to multicellular life (Crockett *et al.* 2024). Despite the harsh environment, the redox state of the paleo-ocean during the glacial period was pulsed, with fluctuations between oxic and anoxic conditions. Glacial melt-oxygen is considered a key factor, as glacial meltwater continuously supplied oxygen to the ice-covered ocean, creating "oxygenated oases" near the ice margins that provided crucial refugia for eukaryotes (Shen *et al.* 2022). The end of Snowball Earth was followed by extreme greenhouse climate. This dramatic environmental shift and the opening of new ecological niches paved the way for the flourishing of the Ediacaran radiation, as well as the subsequent Cambrian Explosion (Casado 2021; Evans *et al.* 2022; Shen *et al.* 2022). Thus, the unhabitable extreme environs of the Snowball Earth lay the foundation for subsequent biotic radiations (Figure 9).

From a tectonic perspective, long-term sustained subduction-accretion orogens and related arc magmatism likely served as the primary drivers of Earth's oxygenation since ~700 Ma. The collision and amalgamation of Gondwana formed super-mountains, triggering intense weathering and erosion, releasing massive sediments and nutrients to the oceans, thereby providing the material basis for the establishment of the modern marine ecosystem (Figure 9). These sediments altered ocean composition and promoted the explosive growth of algae and bacteria, enhanced photosynthesis, and significantly increased marine oxygen levels. During the Ediacaran period, marine phosphorus concentrations experienced pulsed increases (Zhao *et al.* 2024). This was caused by sulfate oxidation of marine organic matter, releasing CO_2 and phosphorus, as well as CO_2-driven terrestrial weathering releasing phosphorus (Dodd *et al.* 2023). High sedimentation rates also improved burial of organic carbon and pyrite, leading to a sustained increase in atmospheric oxygen content. The Gondwana orogen model can better explain the environmental changes at 680–500 Ma. On the other hand, large-scale subduction-accretion improved magmatic degassing and promoted atmospheric CO_2 on a geological scale (Figure 8; Mills *et al.* 2017; Williams *et al.* 2019), which further increased Earth's surface temperature and photosynthetic efficiency. Thus, subduction driven CO_2 degassing raised surface temperatures and enhanced biological activity and productivity. On the other hand, the weathering rate of global orogens consumed atmospheric CO_2 concentrations and modulated the relative stable of atmospheric carbon reservoir. The dynamic balance between these two processes determines the carbon cycle on a geological scale. On the other hand, it provides raw materials for photosynthesis and determines Earth's temperature and influences climate stability. Therefore, the two types of orogenic belts during the Gondwana assembly period served as the sustained, key drivers of Earth's environmental changes in late Cryogenian to the Early Paleozoic.

The extensive exposure of continents above sea level significantly increased the ecological space in coastal and shallow marine areas suitable for the survival of marine life. Orogens lead to changes in geomorphology, which in turn affects the capacity of terrestrial and marine ecosystems, thereby influencing the evolution of biodiversity. Global orogens during the Gondwana period resulted in major geomorphic changes, providing new living spaces and resources for early complex life and promoting the radiation of life. Comprehensive indicators from supercontinent, tectonics, magmatic degassing, the geomagnetic field, environment, biology and ecosystems suggest that the explosive radiation of animal phyla was likely the result of combined external and internal factors, a superposition of countless contingent and necessary factors (Figure 9). External causes included multiple factors from the environmental climate and solid Earth spheres, such as oxygen, paleogeographic ecological space, nutrient elements, Earth's temperature, and the geomagnetic field. The solid Earth sphere, the surface sphere, and even outer space factors collectively constitute the Earth system, driving its evolution.

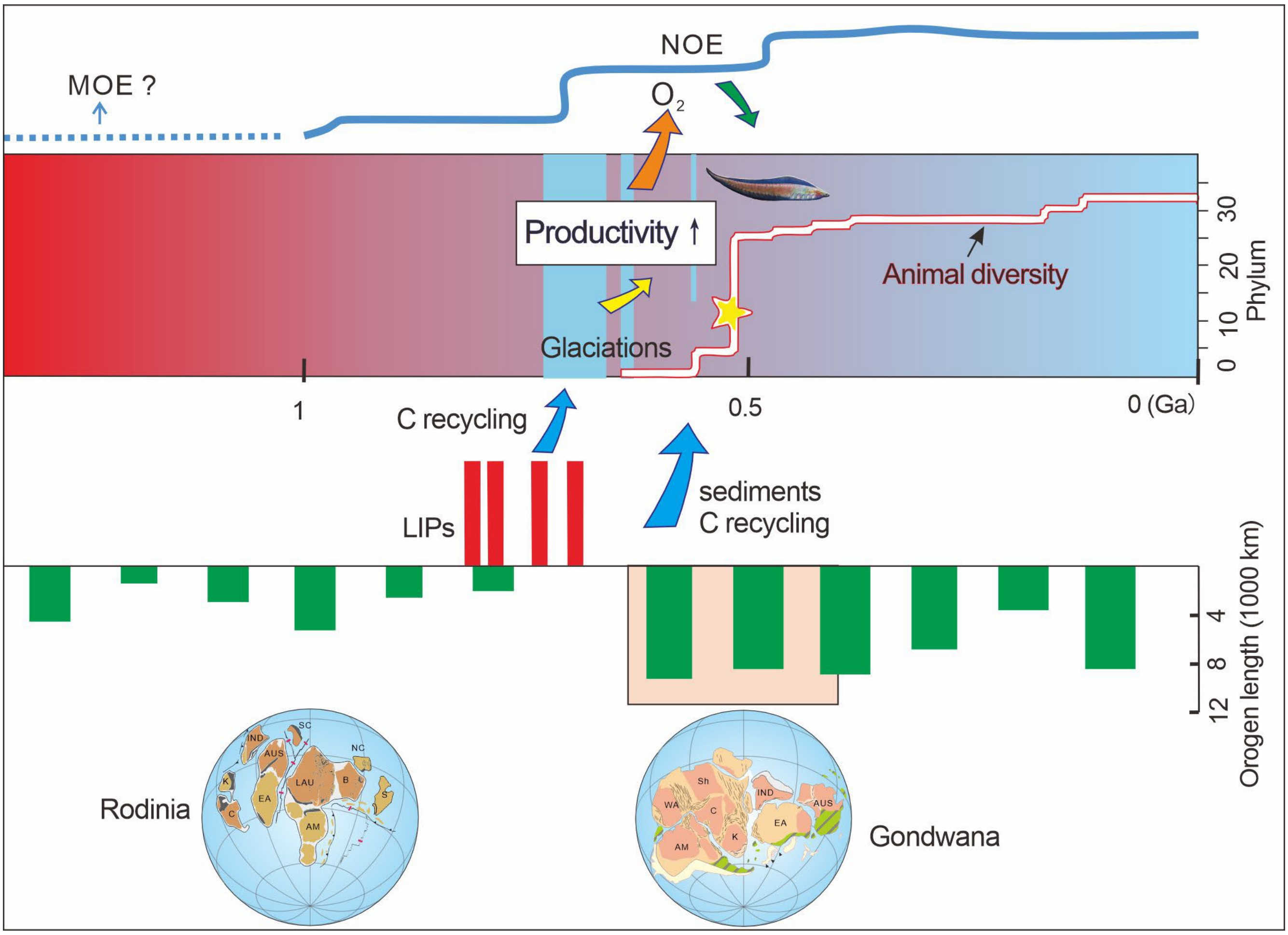

Figure 9. Cartoon for contributions of tectonics to Earth surficial system (data for animal diversity from Zhang *et al.* 2023; the changing atmosphere oxygen levels relative to the present level are after Lyons *et al.* 2021).

9. Conclusion

The breakup of the Rodinia supercontinent triggered Snowball Earth and initiated oxygenation. Subsequently, during the Gondwana assembly, huge orogens under the modern plate tectonic regime provided a sustained and powerful driving force for the tremendous and qualitative changes in the Earth's surface sphere. Moreover, the further significant expansion of the continental geomorphology improved topography to new high level. The exposure of large continental areas provided ecological niches for animal activities. Low-latitude orogenic belts and geomorphology triggered intense weathering and erosion, providing massive amounts of continental margin sediments to the oceans, profoundly altering ocean composition and enhancing marine productivity. Meanwhile, the carbon cycle driven by accretionary and collisional orogeny increased and maintained atmospheric CO_2, promoting the formation of a warm environment and enhancing productivity. In addition, the extreme weak Earth's geomagnetic field intensity in the E-C boundary altered the direction of evolution. The mantle plumes may have served as the initiating trigger, while orogens and subduction zones under the modern plate-tectonic regime during the Gondwana amalgamation, coupled with extreme geomagnetic field, acted as a sustained driving force over geological timescales. This provided the genes, environmental triggers, material basis, and ecological niches for the Ediacaran radiation and the Cambrian Explosion, forming an Earth system of multi-sphere interaction that drove the evolution of the Earth system.

Data availability statement

No supplementary or additional data were generated in this study.

Declaration of generative AI and AI-assisted technologies

The authors did not use generative AI or AI-assisted technologies in the writing of this manuscript.

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Authors' contribution

J.Y.: writing—original draft preparation, result validation, research conceptual design, writing—review and editing, language editing and funding acquisition; Y.H.: research conceptual design and funding acquisition; D.Z.: research conceptual design; Q.L.: practical research investigation; L.C.: dataset arrangement and writing—review and editing; P.C.: dataset arrangement; G.Z.: research conceptual design and funding acquisition. All authors have read and agreed to the published version of the manuscript.

Conflicts of interest

Qian Liu holds the position of Associate Editor for *Continent and Life Evolution* and has not peer reviewed or made any editorial decisions for this paper. The authors declare that no potential conflicts of interest exist for this manuscript. No substantial financial funding was received for the present study that might affect the research results.

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