

Co-Evolution of Life and Plate Tectonics: The Biogeodynamic Perspective on the Mesoproterozoic-Neoproterozoic Transitions

Robert J. Stern^a and Taras V. Gerya^b

^aGeosciences Department, University of Texas at Dallas, Richardson, TX, United States

^bDepartment of Earth Sciences, ETH-Zurich, Zurich, Switzerland

1. Introduction

Life is a wonderful mystery. Science, philosophy, and religion all address the wonder and mystery, but explore them differently. They all ask “Why are we here?” but their approaches are very different. Religion and philosophy probe the meaning of life, whereas science probes life’s origin, mechanisms, and history. In this essay, we follow the second track to explore the co-evolution of life and tectonics on Earth. We do not address the origin of life, which happened 2–3 billion years before the time we are interested in. We focus instead on how a controversial interpretation of Earth’s tectonic history, specifically the emergence of modern plate tectonics that operated in Phanerozoic time (541 Ma–present) from a single-lid tectonic regime in Mesoproterozoic time (1600–1000 Ma)—a transition that took much of

Neoproterozoic time (1000–541 Ma)—helps explain the remarkable acceleration of life evolution during the last quarter of Earth history.

In this paper, we use the following definition of modern plate tectonics (Stern and Gerya, 2018) that emphasizes both its major driving force (oceanic subduction) and difference with other global mobile surface environments (existence of global plate mosaic):

- A global tectonic system powered by subduction in which the lithosphere is divided into a mosaic of strong lithospheric plates, which move on and sink into weaker ductile asthenosphere. Three types of localized plate boundaries form the interconnected global network: new oceanic plate material is created by seafloor spreading at mid-ocean ridges, old oceanic lithosphere sinks at subduction zones, and two plates slide past each other along

transform faults. The negative buoyancy of old dense oceanic lithosphere sinking in subduction zones mostly powers plate movements.

Other mobile surface environments, in which (i) localized plate boundaries do not exist or do not form a global plate mosaic and (ii) any horizontal surface motions are not predominantly driven by oceanic plate subduction we prefer to classify in a very generic manner as “single-lid” tectonics (Stern et al., 2018). Our rather restrictive definition of modern plate tectonics is introduced to discriminate the global regime of the present Earth from that of Venus, where local retreating subduction is induced by plume–lithosphere interactions (e.g., Davaille et al., 2017; Gulcher et al., 2020) and regional horizontal motions of craton-like domains are driven by convective mantle flow (Harris and Bedard, 2015). A single-lid tectonic regime has been proposed for the Precambrian Earth (e.g., van Kranendonk, 2010; Gerya et al., 2015; Harris and Bedard, 2015) including the Mesoproterozoic Eon (Stern, 2020).

In our short review, we first explain what is Biogeodynamics, then review how biological evolution accelerated during the Neoproterozoic Era. Next, we explain what is single-lid tectonics and how this differs from plate tectonics and summarize evidence that the modern plate tectonic regime emerged during the Neoproterozoic from a Mesoproterozoic single-lid tectonic episode. We use biogeodynamic perspectives to explore how this tectonic revolution stimulated biological evolution. Finally, we suggest some avenues for future research.

2. Biogeodynamics

Growing evidence suggests that Earth’s geodynamic evolution has controlled the evolution of its atmosphere, oceans, landscape, and life (e.g., Dehant et al., 2019; Sobolev et al., 2011;

Stern, 2016; Zaffos et al., 2017). Logically, this frontier research direction appears among the top 10 research questions shaping Twenty-first-century Earth Science: “How has life shaped Earth – and how has Earth shaped life? The exact ways in which geology and biology influence each other are still elusive. Scientists are interested in life’s role in oxygenating the atmosphere and reshaping the surface through weathering and erosion. They also seek to understand how geological events caused mass extinctions and influenced the course of evolution.” This short summary lays down the principal foundations of *Biogeodynamics* that explores the interface between the disciplines of geodynamics, geomorphology, climate, ocean and atmosphere sciences, geobiology, and ecology with special focus on how evolution of the planetary interiors, surface, atmosphere, ocean, climate, and life are intrinsically interrelated. This emergent field aims to understand and quantify these dazzlingly complex relationships by combining observational and modeling approaches, and development of new hybrid computational tools (e.g., Leprieur et al., 2016; Pellissier et al., 2017; Descombes et al., 2018) in which a myriad of physical, chemical, biological, atmosphere, ocean, climate, and geomorphological processes are coupled. In particular, Biogeodynamics seeks to investigate different plausible global and regional geodynamic evolution scenarios to gage their influence on biosphere evolution as expressed by biodiversity. We emphasize that biogeodynamic approaches are also useful for exploring other terrestrial and extrasolar planets, for which several contrasting global tectono-magmatic evolution scenarios have been proposed (e.g., Van Heck and Tackley, 2011 and references therein).

There is an emerging consensus that life evolution dynamics varied through geological time and that variations in geographic distribution and diversity of species were strongly affected by contemporaneous changes in Earth’s global tectono-magmatic style (e.g., Stern, 2016;

Zerkle, 2018). The rate of speciation must vary tremendously between organism groups. For instance, the rate must be much higher for microbes than it is for mammals. Importantly, timescales of biological evolution for multicellular organisms estimated on the basis of the analysis of phylogenies and/or fossils are long, similar to geodynamic timescales (e.g., Alroy, 2008; Marshall, 2017). In a constant rate birth–death model (Kendall, 1949), new species originate with speciation rate, and species disappear with extinction rate, typically expressed as rates per lineage per million years ($L^{-1}\text{Myr}^{-1}$). Typically, estimates of speciation and extinction rates range between 0 and $1L^{-1}\text{Myr}^{-1}$ (Marshall, 2017) and rarely exceed $1L^{-1}\text{Myr}^{-1}$, except within intervals of crisis (Alroy, 2008). The timescales of biological evolution are therefore similar to timescales of tectono-magmatic lithospheric and mantle processes in general and plate tectonic motion timescales in particular.

The influences of global tectono-magmatic style are at least two-fold and regulate (A) supply and withdrawal of nutrients (via mantle degassing/ingassing, rock weathering and erosion, sedimentation and burial, subduction-related recycling, etc.) and (B) space–time variations of environmental pressures (including evolution of landmass distribution, landscape, atmosphere, ocean, and climate). Zerkle (2018) and Stern (2016) summarized the interrelated nutrients–tectonics and environmental pressures–tectonics aspects of biogeodynamic coupling, respectively, as:

- Life is sustained by a critical set of elements contained within rock, ocean, and atmosphere reservoirs and cycled between Earth’s surface and interior via various tectonic, magmatic, and surface processes. Over geologic timescales, tectono-magmatic processes play a critical role in providing bioactive elements to the ocean–biosphere

system, via outgassing, volcanism, uplift, and erosion (Zerkle, 2018).

- Tectonic processes such as the redistribution of continents, growth of mountain ranges, formation of land bridges, and opening and closing of oceans provide continuous but moderate environmental pressures that isolate and stimulate populations to adapt and evolve without being capable of extinguishing all life. Plate convergence can also lead to extinction of life forms that cannot compete with others they are brought into contact with due to plate interactions that create new land bridges and seaways.

In addition, mantle plumes and large bolide impacts provide episodic but potentially extreme environmental pressures capable of causing global mass extinctions.

To recapitulate, there is growing understanding that modern-style plate tectonics with its global continuously evolving mosaic of lithospheric plates (e.g., Bercovici and Ricard, 2014) acted as a strong promoter of biological evolution (e.g., Leprieur et al., 2016; Pellissier et al., 2017; Descombes et al., 2018; Zerkle, 2018) that we explore here.

3. Modern plate tectonics and biodiversity evolution

Before discussing how changes in global tectonic style through geological time may have affected the terrestrial life evolution, we first summarize recent findings on how present-day tectono-magmatic style—modern plate tectonics—interacted with life evolution through recent geological time, for which a robust paleontological record is available.

One of the key features of the modern-style terrestrial biosphere is a strong non-random geographical variability of different species distribution on Earth’s surface and in its oceans

(e.g., Willig et al., 2003; Gotelli et al., 2009; Defosse et al., 2021; Keith et al., 2013). However, the mechanisms that generate and maintain species richness gradients at macroecological scales remain unresolved (e.g., Willig et al., 2003; Gotelli et al., 2009; Defosse et al., 2021; Keith et al., 2013) and understanding the mechanistic basis of these patterns remains the “holy grail” of modern biogeography and macroecology (Willig et al. 2003). As summarized by Pellissier et al. (2017), ecological and evolutionary theories recognize that uneven spatial distribution of biodiversity is the product of both contemporary and historical factors (Latham and Ricklefs, 1993; Mittelbach, 2007). In particular, plate tectonics has been shown to foster species diversification in geologically active regions (Bagley and Johnson, 2014; Magri et al., 2006; Pellissier et al., 2017; Richardson et al., 2014). The concordance between extant species richness and topographical variability (Davies et al., 2007), spatial environmental heterogeneity (Stein et al., 2014), tectonic plate boundaries, and mantle plume tracks (Keith et al., 2013) has also been documented suggesting the strong influence that plate tectonics and related geological and geomorphological processes play in shaping the evolution of global biodiversity.

There are several key features of modern-style plate tectonics that may have critically shaped evolution of species richness and biodiversity patterns on Earth (e.g., Pellissier et al., 2017; Stern, 2016 and references therein):

- The presence of slowly but continuously moving mosaic of tectonic plates including both continental and oceanic lithospheres, surrounded by an evolving network of convergent, divergent, and transform plate boundaries.
- Operation of the global Wilson cycle that causes breakup and dispersal of continents through opening and widening of new straits and oceans by continental rifting and oceanic spreading followed by their closure due to subduction and continental collision, leading to re-assembling of continents in different configurations.
- Topographic changes related to plate convergence (Defosse et al., 2021; Hoorn et al., 2010; Toussaint et al., 2014). In particular, orogenic processes build complex topography and precipitation patterns in plate convergence zones. Changing topography acts as a biodiversity pump (Badgley, 2010).
- Topographic changes related to plate rifting, breakup, and divergence that isolate populations with oceanic gateways, fueled by sporadic events of dispersal across straits (Lavergne et al., 2013). New oceans provide new habitats that also stimulate marine biodiversity. Plate divergence may thus represent a major catalyst of speciation (Steeman et al., 2009).
- The development of island chains by magmatism along subduction zones and mantle plumes tracks that complicate ocean circulation and tidal patterns and provide dry land connectivity paths between continents. The emergence of new volcanic islands associated will also contribute to species diversification through allopatric speciation (Bidegaray-Batista and Arnedo, 2011; Briggs, 2003).
- Long-term moderate magmatic activity along plate boundaries that contribute to the long-term climate and atmosphere evolution (e.g., Brune et al., 2017 and references therein). Explosive volcanism at convergent margins is especially important for injecting S into the stratosphere and spreading inorganic nutrients via ash dispersal.
- Rare catastrophes related to new mantle plume activity and the formation of large igneous provinces that may cause abrupt climatic changes and lead to global mass extinction events (e.g., Sobolev et al., 2011).

These events are likely suppressed by plate tectonics, which efficiently cools the upper mantle by cold oceanic plates subduction.

In order to analyze the complex relationship between the tectonics and species richness at both global and regional scales, novel mechanistic modeling approaches are required. Some of the requisite tools have been developed recently (e.g., Leprieur et al., 2016; Pellissier et al., 2017; Descombes et al., 2018). In particular, Pellissier et al. (2017) investigated how changes in the position, connectivity, and topography of continents during the last 100 Myr could have shaped the current location of endemic richness “hotspots” across the globe. They used paleogeographies in a numerical model that quantifies, through time and space, the potential dispersal between disconnected habitat areas. Pellissier et al. (2017) found significant spatial congruence between the model results and modern biodiversity, providing quantitative evidence of the contribution of plate tectonics in shaping global biodiversity. Remarkably, the plate tectonic signal was independent from those of the Quaternary glaciation, topographical heterogeneity, and contemporary productivity and was stronger for terrestrial than freshwater and marine taxa (Pellissier et al., 2017). Complex tectonic regions, predominantly located at the confluence of major lithospheric plates, such as the Mediterranean, Mesoamerica, Madagascar, and South East Asia, likely provided favorable environments for allopatric speciation and the emergence of new species (Pellissier et al., 2017). Non-coincidentally, these are also areas strongly affected by various subduction, collision, and plate tectonic processes and complex landscape evolution.

Based on the recent global and regional analyses and modeling of biodiversity, three main influences of modern plate tectonics on stimulating biological evolution can be identified:

- Plate tectonics creates long-lived complex and versatile marine and terrestrial realms as

well as topography, climate, and precipitation patterns by plate interactions at evolving boundaries. This stimulates the development of biodiversity and intensifies nutrient delivery by erosion.

- Plate tectonics slowly (i.e., on timescales comparable to those for the evolution of complex species) changes these realms and patterns by plate motions. This creates new opportunities for species to adapt, migrate, and interact that stimulate speciation and natural competition.
- Plate tectonics suppresses the most powerful plumes, especially those originating in the upper mantle. This decreases frequency of sudden (i.e., on timescales much shorter than those of biological evolution of complex species) plume-related catastrophic tectonomagmatic events that may cause global mass extinctions.

This recent effort also demonstrates that Biogeodynamic numerical modeling (i.e., coupled modeling of Earth’s interior, climate, environment, and life evolution) stands as one of the frontier research tasks in geodynamics, biology, ecology, and evolution as well as related disciplines. This is a very promising research direction, which will explore connections between deep Earth processes, surface processes, climate, and the diversification of life. Accelerated development and application of new global- and regional-scale computational biogeodynamic numerical modeling tools is needed. These tools should couple (i) available global and regional geodynamic models of subduction and plate-tectonic processes (e.g., Rolf et al., 2012, 2014; Crameri et al., 2012; Gerya et al., 2015), (ii) landscape evolution models (e.g., Brown and Yamato, 2010; Thieulot et al., 2014; Ueda et al., 2015), (iii) atmospheric, ocean, and climate change models (e.g., Donnadieu et al., 2006, 2009) and (iv) spatially explicit models of species speciation, evolution, and extinction (e.g., Gotelli et al., 2009; Leprieur et al., 2016;

Pelliesier et al., 2017; Schluter and Pennell, 2017; Pontarp et al. 2018; Rangel et al., 2018; Descombes et al., 2018; Hagen et al., 2020). The resulting hybrid biogeodynamic numerical modeling tools will be useful for systematic exploration of various subduction and plate tectonics scenarios to understand their potential effects for the evolution of the environment, landscape, climate, and the diversification of life. Such tools should also be modifiable for investigating how landscapes, climate, and life evolve differently in single-lid vs. plate tectonic Earth-like planets. In the next section, we use our developing understanding of these interactions to explore how tectonics and life co-evolved over the last 1.6Ga of Earth history.

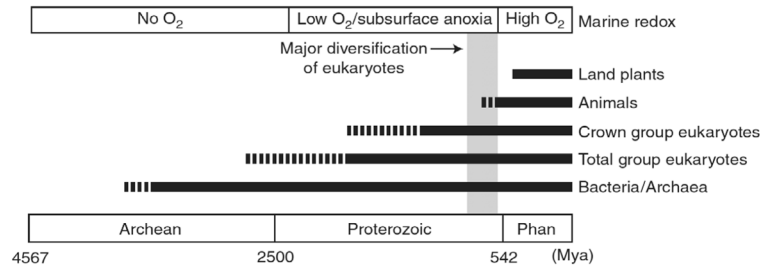
4. Biological evolution in Mesoproterozoic and Neoproterozoic time

Life began sometime prior to the oldest evidence of its existence, ~ 3.8 Ga (Knoll and Nowak, 2017; Fig. 1A). Evolution was slow for the first 3 billion years, dominated by archaea and prokaryotes (bacteria), single-cell organisms that lack the membrane-bound organelles of eukaryotes. These organelles include the nucleus, mitochondria, and chloroplasts. All complex, multicellular life is eukaryotic. Single-cell eukaryotes had to evolve from prokaryotes before multicellular plants and animals could evolve from them. Eukaryote fossils go back to late Paleoproterozoic time and perhaps earlier (Fig. 1A). Because of the importance of oxygen to especially animal metabolism, multicellular animals and oxygenation of the atmosphere and ocean co-evolved. Rising oxygen concentrations as a result of the Great Oxygenation Event (GOE) 2.4 billion years ago facilitated the emergence of eukaryotes.

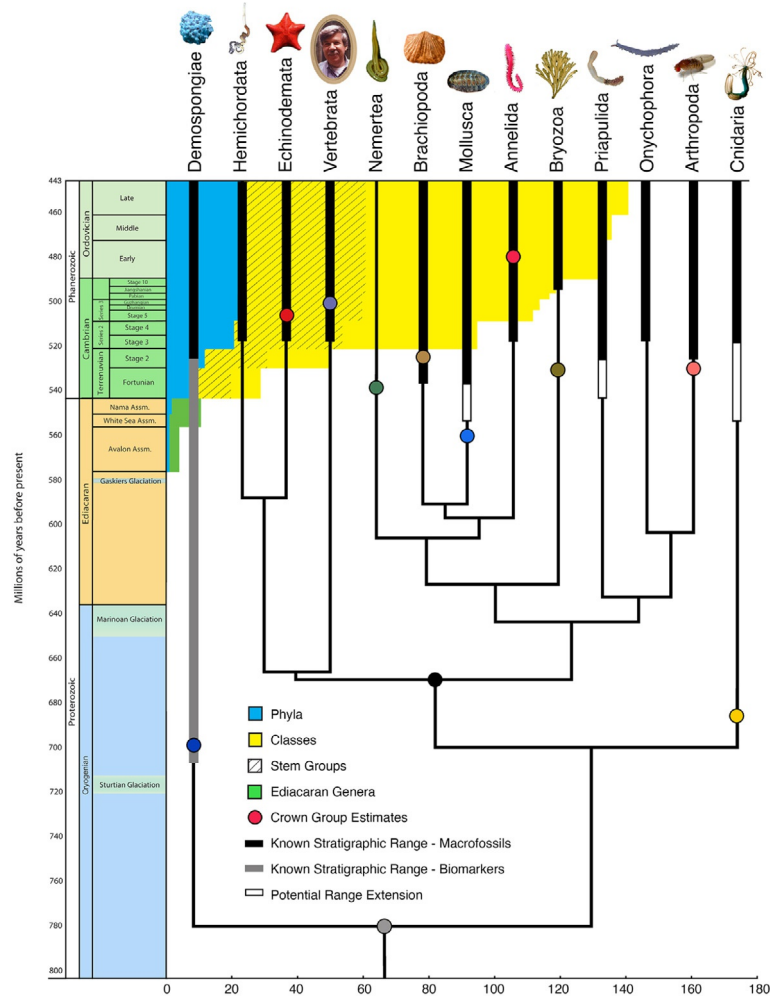
We pick up the story at ~ 1.6 Ga, at the beginning of the Mesoproterozoic Era. There are no “big events” that naturally define when Mesoproterozoic time began and ended and

what are its natural subdivisions (periods). The IUGS Subcommittee on Precambrian Stratigraphy first recommended subdividing Proterozoic time into three eras: Proterozoic I (2500–1600Ma; now Paleoproterozoic), Proterozoic II (1600 and 900Ma; now Mesoproterozoic), and Proterozoic III (900 to Cambrian; now Neoproterozoic) (Plumb and James 1986). The Subcommittee defined the beginning of Mesoproterozoic time by the waning of tectonic activity. Plumb and James (1986, p.82) noted “The boundary between [Paleoproterozoic] and [Mesoproterozoic] is geologically somewhat diffuse and, within the Subcommittee, individual preferences for a bounding age ranged from 1400 to 1800 Ma. The selected value of 1600 does, however, record the approximate termination of the whole complex of events associated with and following the [Paleoproterozoic] orogenies...” The young time boundary for Proterozoic II at 900Ma was “...selected to provide the upper age limit for the intense crustal disturbance and magmatism in [Grenville and related] mobile belts (Plumb and James, 1986, p. 83).” The IUGS finally adopted an end to the Mesoproterozoic at 1000Ma.

One could argue that the Mesoproterozoic Era should have an earlier start and a later end because it is the heart of the “Boring Billion” (between ~ 1800 and 800Ma). This term was coined by Holland (2006) because atmospheric oxygen levels did not change much during this time. The term now is used to describe many other aspects about this episode of Earth history. It is now used to describe a time of geobiological stasis, including a remarkably stable carbon isotope trend in sedimentary rocks. Other indications of extended environmental stability are captured in S, Mo, Cr, Sr isotopes, and more particularly, by low values of trace element concentrations and P in marine black shales. This protracted stable period— $\sim 20\%$ of Earth history—is also interpreted to reflect a prolonged lack of nutrient supply (Mukherjee et al., 2018).



(A)



(B)

FIG. 1 Evolution of life. (A) A summary of early eukaryotic evolution. Solid bars denote confident interpretation of geologic record; dashed bars indicate uncertain or controversial extensions of the record. Phan, Phanerozoic Eon (literally, the age of visible animal life; Knoll, 2014). (B) Detailed stage-level depiction of the animal fossil record as compared to the molecular divergence estimates for 13 different animal lineages (top; from Erwin et al., 2011). Shown in yellow and blue is the known fossil record of animals at the class and phylum levels, respectively (hatching indicates “stem” lineages, i.e., specific phylum but not to any of its living classes); shown in green is the generic record of macroscopic Ediacara fossils (see scale at bottom). *Thick black lines* are the fossil records of each of these 13 lineages through Cryogenian–Ordovician time; most lineages make their first appearance in the Cambrian, consistent with the animal fossil record (*yellow and blue*). Further, the extent of these stratigraphic ranges closely mirrors the molecular estimates for the age of each of the respective crown groups (*colored circles*), highlighting the general accuracy of the molecular clock. Only cnidarians have an unexpectedly deep crown-group origination as estimated by the molecular clock.

There was life in the Mesoproterozoic but evolution was sluggish, especially compared to the spectacular evolution of Neoproterozoic and Phanerozoic time. Microfossils (~100 μm in size) in Mesoproterozoic sedimentary rocks include modestly diverse specimens of probable eukaryotic origin (Knoll and Nowak, 2017), but evidence from microfossils, chemical fossils (mostly lipid “biomarkers”), and stromatolites indicates that marine productivity was monopolized by cyanobacteria (Butterfield, 2015). Geochemical proxies indicate oceanic stratification, with significant oxygen in the atmosphere (1%–10% present atmospheric levels, PAL) and in the shallow, wind-mixed ocean, but widespread anoxia deeper. Stromatolites—colonial cyanobacteria that built calcareous mounds—were the biggest Mesoproterozoic organisms. These rose to prominence in Paleoproterozoic and Mesoproterozoic time and declined in importance throughout Neoproterozoic time (Fig. 2).

The Neoproterozoic contrasts markedly with the Mesoproterozoic in being a time of climate instability and rapidly evolving life. Holland (2006) said “If it is apt to describe [the time period from 1.85 to 0.85 Ga] as boring, then [the Neoproterozoic] was blustery and baleful.” The Neoproterozoic—especially its last

180 Ma—was as exciting as the previous billion years were boring. Neoproterozoic strata host evidence of global “Snowball Earth” glaciations, large perturbations to the carbon cycle, oceanic oxygenation, the diversification of microscopic eukaryotes, and the rise of metazoans (Fig. 3; Cohen and Macdonald, 2015). The Neoproterozoic Era is subdivided into three periods: the Tonian (1 Ga–720 Ma), the Cryogenian (720–635 Ma), and the Ediacaran (635–541 Ma). The much longer Tonian period was more stable, more like the Mesoproterozoic era than the much shorter and more exciting Cryogenian and Ediacaran periods (Butterfield, 2015).

Evolution accelerated in Neoproterozoic time (Butterfield, 2015). Carbon isotopic composition of seawater varied more wildly than at any other time in Earth history (Fig. 3; Butterfield, 2015). Eukaryotes rose in prominence and complexity beginning in Cryogenian time (Fig. 1B). Biomarker data show that eukaryotic contributions to primary productivity increased markedly about this time. Molecular clocks suggest a Cryogenian diversification of eukaryotes that led to the evolution of metazoan (animals) (dos Rios et al., 2015), although body fossils occur only in Ediacaran and younger rocks. Protist (eukaryotic) diversity begins to show armored testes, suggesting that predators had

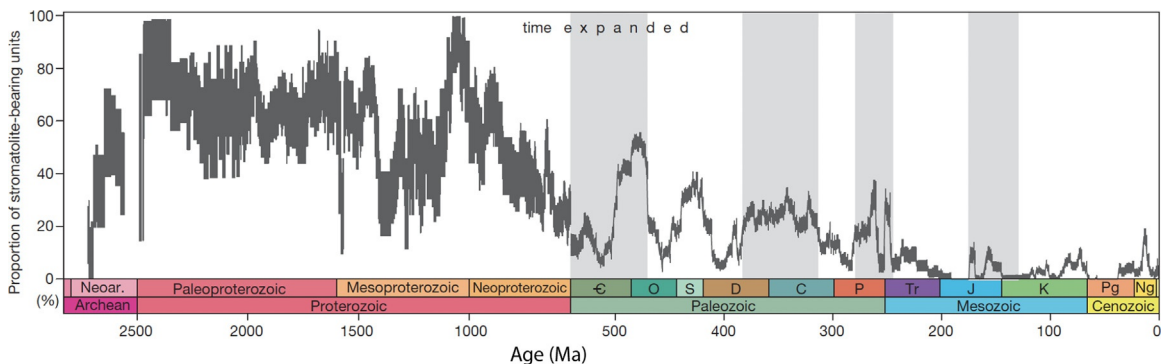


FIG. 2 Occurrence of stromatolites in North America and the Caribbean. Proportion of stromatolite-bearing units are normalized by marine sedimentary rock units. 100% indicates all rock strata deposited at that time contain stromatolites. After Lee, J.H., 2021. *Stromatolites*. *Encyclopedia of Geology*, second ed. 375–388.

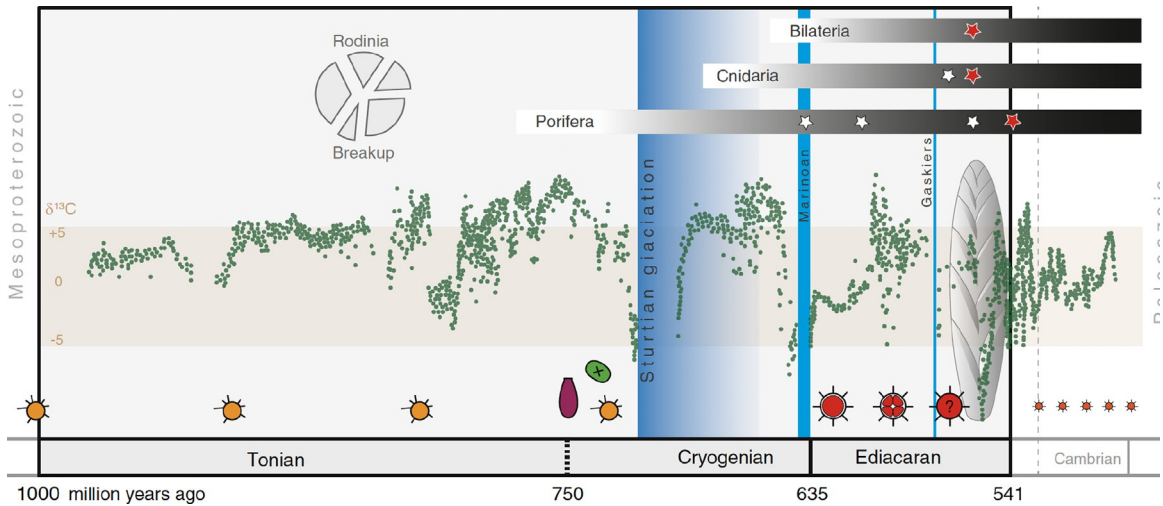


FIG. 3 Diagram of the Neoproterozoic Era illustrating the large-scale correlation between evolutionary innovation, climate perturbation, and trends in the $\delta^{13}\text{C}$ of marine carbonates (a reflection of the global carbon cycle). Patterns in the distribution of protistan-grade fossils are depicted below the $\delta^{13}\text{C}$ curve and include pre-Cryogenian ornamented microfossils (*orange*; typically asymmetrical, moderately large and stratigraphically long-lived), “vase-shaped” microfossils (*purple*), scale microfossils (*green*), Ediacaran-age ornamented and “embryo” microfossils (*red*; typically symmetrical and large, with “embryos” sometimes occurring within the lumen of ornamented forms), Ediacaran macrofossils (*gray*), and ornamented Cambrian microfossils (*dark orange*; typically symmetrical and small). Bars above the $\delta^{13}\text{C}$ curve represent molecular clock estimates for the first appearance of major metazoan groups (from Erwin et al. 2011), with *white stars* marking the first “suggestive” occurrence of corresponding fossils, and *red stars* indicating first “convincing” occurrence of such fossils, from Butterfield (2015). The boundary between the Tonian and the Cryogenian is at 720Ma. The dashed line at ~530 million years ago marks the onset of rapid evolutionary change, and regime shift into recognizably Phanerozoic style ecological and evolutionary dynamics, the “Cambrian Explosion,” as well as return to the relatively stable $\delta^{13}\text{C}$ of the early Tonian. The end of the Neoproterozoic Era (and Proterozoic Eon) is the beginning of the Paleozoic Era (and Phanerozoic Eon).

evolved to eat them. Plants also evolved rapidly, with diversification of complex multicellular red and green algae (seaweeds). All of the important lineages of animals existed less than 200 million years later, at the beginning of Phanerozoic time at 541 Ma.

5. Mesoproterozoic single lid and the Neoproterozoic transition to plate tectonics

For some time after the plate tectonic revolution occurred in the late 1960s, it was difficult for geoscientists to imagine any other convective style for Earth and other active silicate

bodies. Two advances changed this failure of imagination. The first came from exploring planets and moons in the Solar System, especially orbital radar imaging of the surface of Earth’s twin, Venus, by the Venera 16 (1983) and especially the Magellan (1989–1994) spacecraft. Its surface clearly showed abundant deformation and volcanism but not plate tectonics (e.g., Smrekar et al., 2018; Harris and Bedard, 2015; Gulcher et al., 2020). Exploration of Mars and Jupiter’s innermost moon Io provided other examples of actively convecting (active) silicate bodies that do not have plate tectonics; these bodies have “single-lid” tectonic styles (Stern et al., 2018). Single-lid tectonics contrasts with plate tectonics by having a single, unfragmented

(i.e., with no well-defined global network of tectonically active localized plate boundaries), all-encompassing lithosphere. Active single-lid tectonic regimes can be just as tectonically and magnetically active as plate tectonic regimes and can recycle surface materials into the mantle by various processes such as plume-induced subduction (e.g., Gerya et al., 2015; Gulcher et al., 2020). Single lid is often called “stagnant lid,” but this term does not capture the dynamic nature of active single-lid bodies. We are only beginning to explore the range of active silicate body single-lid behaviors and terminology is still confusing. O’Neill and Roberts (2018) refer to stagnant, sluggish, plutonic squishy, or heat pipe variants, whereas Fischer and Gerya (2016a) refer to plume-lid tectonics. “Sagduction”—the vertical sinking of weak lithosphere—is another vigorous non-plate-tectonic style (Nédélec et al., 2017). Solar System exploration demonstrated that plate tectonics is not occurring on the three other active planets and moons (Venus, Mars, Io), suggesting that it is also unusual in Earth history. It should be noted that there may be other types of plate tectonic like behavior—peeling off tectonics—that has been suggested for hotter Precambrian Earth based on numerical models, e.g., Chowdhury et al. (2017). A possible scenario using these insights is shown to explain Earth’s tectonic evolution in Fig. 4.

The second advance was a better understanding of the driving forces for plate tectonics. Geodynamicists increasingly agree that it is not mantle convection currents that drives especially oceanic plate motions, it is the sinking of dense oceanic lithosphere in subduction zones that is mostly responsible, although deeper mantle currents may drag the deep lithospheric roots of the slowly moving continents. Understanding driving forces allowed us to better infer what conditions are needed for plate tectonics to occur. Plate tectonics requires “Goldilocks conditions” of lithospheric density, strength, and lubrication: oceanic lithosphere must be denser than underlying asthenosphere and must be strong enough to hold together during

subduction so that the subducted portion can pull the surface portion but not so strong that it cannot be broken into new plates or segmented at trenches causing frequent slab break-off and precluding continued subduction. Surface water buried in hydrated upper oceanic crust also plays a key role in plate tectonics by lubricating convergent plate boundaries, enabling continued one-sided oceanic subduction, and generating water-rich arc magmas (Gerya et al., 2008, Cramer et al., 2012). The nature of oceanic lithosphere density and strength that exist early in Earth’s evolution, when its interior is hot, oceanic crust is thick and mantle lithosphere is thin and weak, do not favor the establishment of plate tectonics. Conditions of oceanic lithosphere suitable for plate tectonics are only likely later, after Earth’s interior has cooled by hundreds of °C (e.g., Sizova et al., 2010, 2014, 2015; Johnson et al., 2014; Fischer and Gerya, 2016a,b; Chowdhury et al., 2017).

Earth has always experienced deformation and magmatism, but this does not require plate tectonics. Because Earth is a high energy, far-from-equilibrium system, its tectonic style must have emerged with time (Stern and Gerya, 2021; see video https://www.youtube.com/watch?v=d939_DDU0w8). Earth’s tectonic evolution was complicated, with multiple episodes of different active single-lid tectonics and of something similar to modern plate tectonics. Different tectonic regimes produce different structures, metamorphic rocks, and igneous rocks that, if preserved, provide evidence about the tectonic regime that produced them. Reconstructing Earth’s tectonic history becomes increasingly difficult the farther we go back in time because erosion removes evidence, old rocks get buried by young rocks, and later tectonic, magmatic, and metamorphic episodes overprint older evidence. Erosion, burial, and overprinting destroy some but not all of the evidence of past tectonic regimes, at least for the past 3.8Ga. It is conceivable that erosion could remove all evidence of shallow features such as porphyry copper deposits and ophiolite nappes

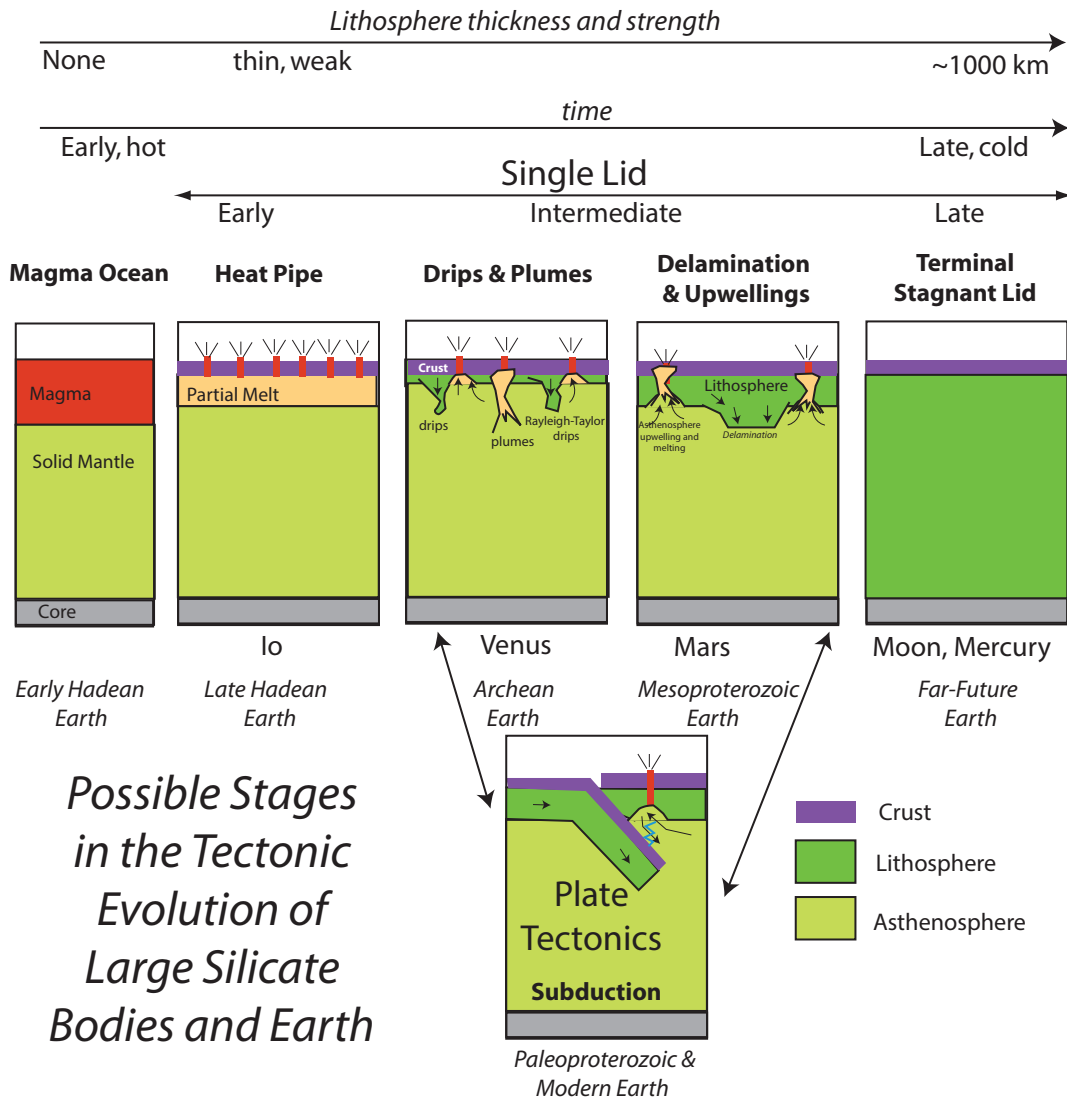


FIG. 4 Possible evolution of magmatotectonic styles for a large, cooling silicate body using Earth as an example, with reference to active Solar System bodies Io, Venus, and Mars. Cooling leads to the formation of crust followed by the formation of mantle lithosphere, which thickens and strengthens with time. Strength of internally driven mantle convection is indicated by *arrowed curve* thickness, which weakens with time as mantle cools and becomes more viscous. Plate tectonics requires certain conditions of lithospheric density and strength in order to occur. Plate tectonics is likely to be presaged and followed by different styles of stagnant lid tectonics; last panel is for a “dead” body like Moon or Mercury. See text for further discussion. Modified after Stern, R.J., 2020. *The Mesoproterozoic single lid tectonic episode: prelude to plate tectonics*. *GSA Today* 30 (12), 4–10.

but it is impossible for it to extirpate evidence from intrusive and metamorphic rocks, which extend to much greater depth. Microscopic, geochemical, and isotopic evidence may be useful for identifying when a change occurred in

Earth’s convective style but cannot reliably constrain when plate tectonics began, unless the only significant change was the start of plate tectonics. [Condie \(2018, p. 58\)](#)’s admonition “...recycling of crust into the mantle does not necessarily require

subduction, and it may be possible for such recycling to occur in stagnant [single]-lid regimes....” should be kept in mind.

We can best reconstruct Earth’s tectonic evolution working backward in time from the present because we know what the tectonic style is now; working backward in time lets us first identify when a significant change happened and then interpret its significance. The first step that needs to be taken is to not assume that plate tectonics has always occurred on Earth and to start thinking about Earth tectonics as an emergent system (Stern and Gerya, 2021). There is abundant geologic evidence that Earth’s modern plate tectonic regime began in Neoproterozoic time (Stern, 2018). If so, it follows that Earth did not have plate tectonics in Mesoproterozoic time and must have had some type of single-lid tectonics. Can this claim be tested? Geologic evidence—both negative and positive—should guide our interpretation of Mesoproterozoic tectonics. Negative evidence shows an absence of three groups of key plate tectonic indicators of seafloor spreading and subduction initiation, subduction, and continental collision. These plate tectonic indicators are ophiolites, blueschists, lawsonite-bearing metamorphic rocks, jadeitite, ultra-high-pressure metamorphic rocks, and rubies and sapphires (Fig. 5B–D). Positive evidence focuses on three indicators of single-lid behavior; two types of unusual dry magmas (A-type granites and anorthosite massifs), evidence of a warming interior due to single-lid insulation of Earth’s mantle, and an absence of evidence of new passive continental margins (Fig. 5E–H). The first approach is straightforward because we know the kinds of minerals, rocks, and rock sequences that plate tectonics produces. The second approach is more difficult because we are only beginning to think about what should be produced and preserved by active single-lid tectonics.

A few words about the compilations shown in Fig. 5 are needed. First, these compilations emphasize large-scale geologic features, not trace element ratios or isotopes. This is because changes in trace element ratios and/or isotopes may reliably indicate that some change in Earth’s tectonic style happened but cannot tell that change was the start of plate tectonics; such a change could be from one single-lid tectonic style to another. Instead, geologic features, rocks, and minerals that are uniquely formed by plate tectonic processes—like ophiolites, blueschists, and rubies—are emphasized. Second, in an effort to ensure objectivity, the compilations we show are not our own but from the peer-reviewed literature. Finally, multiple proxies should be considered. Because the geologic record is incomplete due to erosion, burial, and metamorphism, the record of no single feature can be trusted; instead multiple proxies should be used. Comparing multiple proxies builds confidence that removal by erosion, metamorphic overprinting, or other ways of disturbing the record has not happened.

Consider the negative evidence first. Stern (2018) identified three groups of rocks and minerals that only form by plate tectonic processes. These are (1) ophiolites, indicators of subduction initiation and seafloor spreading; (2) blueschists, lawsonite-bearing metamorphic rocks, and jadeitite, all three indicators of subduction; and (3) ultra-high-pressure (UHP) metamorphic rocks along with ruby and sapphire, indicators of continent-continent collision (Fig. 5B–D). These three groups of plate tectonic indicators are abundant in Phanerozoic and Neoproterozoic rocks and are missing from the Mesoproterozoic record. There are some ~1.8–2.0 Ga plate-tectonic indicators, suggesting that an episode of proto-plate tectonics happened then. The metamorphic record provides another robust indicator of Earth’s tectonic behavior over time. Brown and Johnson (2018) compiled data for 456 metamorphic terranes from the Eoarchean to the Cenozoic

Climate Stability Indicators

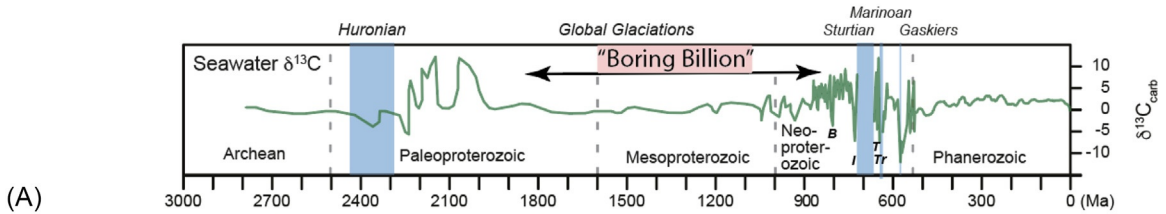
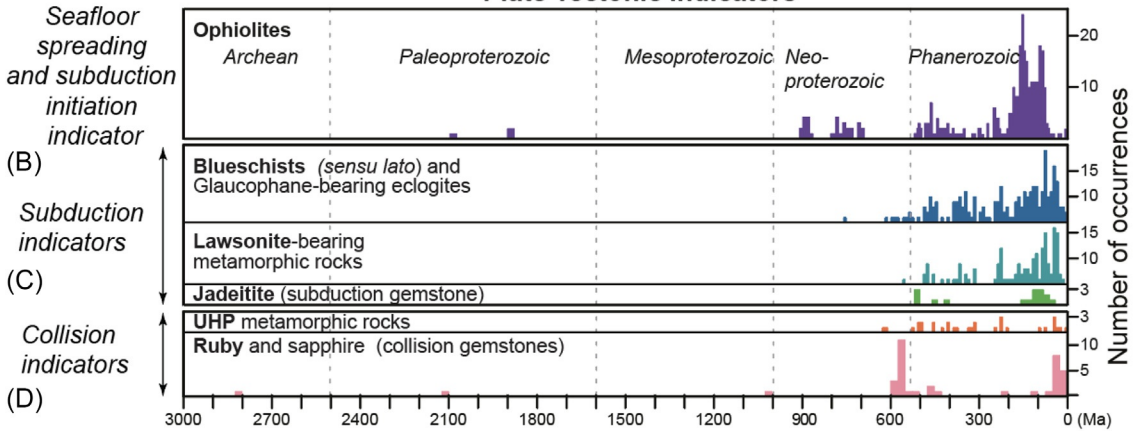


Plate Tectonic Indicators



Single Lid Indicators

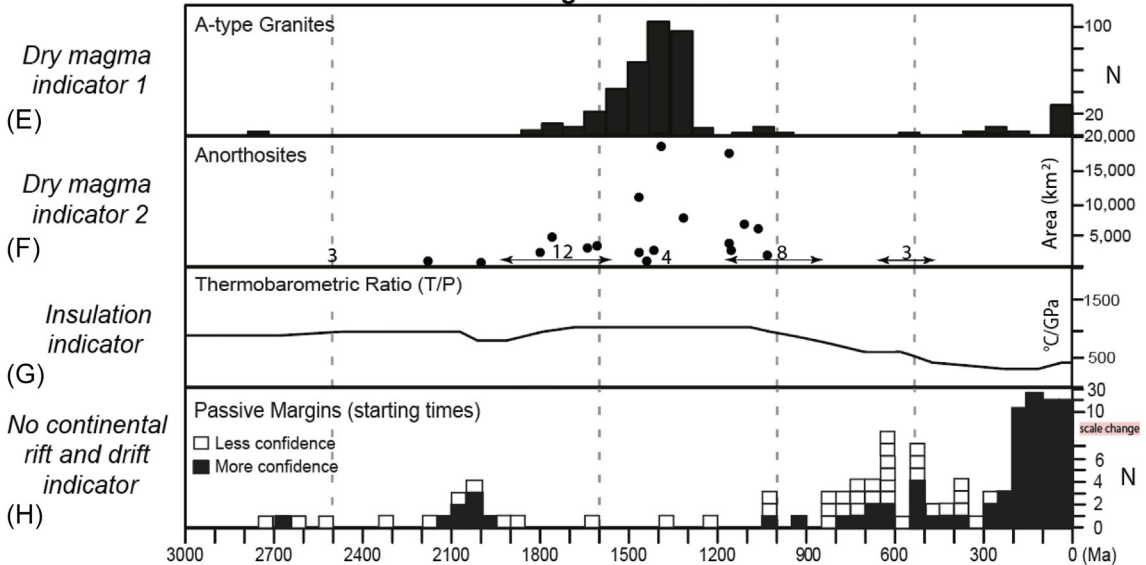


FIG. 5 (A) Climate, (B–D) plate tectonic, and (E–H) single-lid indicators for the past 3.0 Ga of Earth history. Climate stability and plate tectonic indicators from Stern (2018). “Boring Billion” from Holland (2006). Single-lid tectonic indicators include (E) A-type granites (Condie 2014), (F) massif type anorthosites (Ashwal and Bybee, 2017), (G) thermobarometric ratios ($N = 564$; best fit curve from Brown et al., 2020), and (H) numbers of passive continental margins (Bradley, 2011). Fourfold confidence subdivision of Bradley (2011) is simplified into two intervals of higher and lower confidence.

and classified these into 3 groups. Low dT/dP metamorphic rocks correspond to blueschist and eclogite that only form in subduction zones. There are a few low dT/dP metamorphic rocks ~ 1.9 Ga but almost none in the Mesoproterozoic. There are a lot of Neoproterozoic and Phanerozoic low dT/dP metamorphic terranes. An independent assessment by [Palin et al. \(2020\)](#) confirms that there were two great episodes of low dT/dP metamorphism: a minor one at 1.8–2.1 Ga and a second major episode which began 0.7 Ga and continues today. The Paleoproterozoic episode of proto-plate tectonics may have ended with the assembly of a supercontinent (Columbia or Nuna; [Rogers and Santosh, 2002](#)). The formation of supercontinents destroys subduction zones and thus favors the establishment of single-lid tectonic regimes ([Silver and Behn, 2008](#)), and this may have led to the protracted Mesoproterozoic single-lid episode.

Positive evidence for single-lid behavior includes three types of indicators ([Stern, 2020](#)): (1) geochemical evidence of unusual, dry magmatism; (2) metamorphic evidence of elevated heat flow; and (3) lack of sedimentological evidence for the formation of new passive continental margins. These are considered in greater detail below.

Because plate tectonics and subduction zones deliver a lot of water deep into the mantle ([van Keken et al., 2011](#)) and single-lid episodes deliver less water, magmas generated during single-lid episodes should be drier than arc magmas generated by plate tectonics. I-type granitic rocks should dominate during plate tectonic regimes. In contrast, A-type granitic rocks are anhydrous, alkali-rich, and anorogenic A-type granites ([dall’Agnol et al., 2012](#)). Mesoproterozoic A-type granites are unusually abundant compared to earlier and later times ([Fig. 5E](#)). Massif-type anorthosites are another indicator of unusual anhydrous magmas; they may reflect deep-crustal ponding of anhydrous basaltic magmas (which are enriched in Fe during fractionation), crystallization and sinking of

mafic minerals, and flotation of plagioclase in Fe-rich magma ([Namur et al., 2011](#); [Ashwal and Bybee, 2017](#)) or partial melting of basaltic crust in eclogite facies ([Bedard, 2010](#)). Massif-type anorthosites are rare in Neoproterozoic and Phanerozoic times but abundant in the Mesoproterozoic ([Fig. 5F](#)).

A second line of positive evidence is that the lithosphere heated up in Mesoproterozoic time. This is shown by the metamorphic thermobaric ratios (temperature/pressure, T/P) for Paleoproterozoic to Cenozoic metamorphic rocks ([Brown et al., 2020](#)). Thermobarometric ratios over the past 3.0 Ga are highest for Mesoproterozoic time ([Fig. 5G](#)). Heating up of the upper mantle (and the overlying lithosphere) is expected for single-lid tectonic regimes. As previously noted, plate tectonics cools Earth faster than single lid because it injects cold lithosphere deep into the mantle in subduction zones at the same time it releases asthenospheric heat at spreading ridges. An all-encompassing single lid, in contrast, insulates the interior and traps heat in the asthenosphere. Heat release is accomplished by magmatic outbursts and thinning the lithosphere ([van Thienen et al., 2005](#)). Lithospheric thinning leads to an elevated thermal gradient that is preserved in metamorphic rocks.

The third line of evidence is the paucity of new passive continental margins that formed in Mesoproterozoic time ([Fig. 5H](#); [Bradley, 2011](#)). Passive continental margins are a key aspect of the Wilson Cycle: they form when continents rift and drift apart. Passive continental margins form frequently in a plate tectonic regime but not in a single-lid tectonic regime.

There are also distinctive Mesoproterozoic ore deposits that do not form in younger times when we can be confident that plate tectonics occurred, including sedimentary rock-hosted U, Kiruna magnetite–apatite, iron oxide–copper–gold (IOCG), and ilmenite ore deposits. Correspondingly, the Mesoproterozoic lacks ore deposits that are common to younger assemblages formed by plate tectonic processes such

as orogenic gold and porphyry copper deposits (Goldfarb et al., 2010). Different mineralization styles are expected to accompany different tectonic styles. The contrast between younger plate tectonic-related and Mesoproterozoic mineralization styles could not be greater, consistent with an interpretation of different tectonic styles for these intervals.

Finally, there is paleomagnetic evidence. Paleomagnetic measurements could resolve the controversy because for single-lid behavior, this should show that all continental blocks moved together. Unfortunately, paleomagnetic data that bear on this question are equivocal. Evans and Mitchell (2011) compiled existing and reported new paleomagnetic data and used these to conclude that there were "... minimal paleogeographic changes across Earth's first supercontinent cycle, in marked contrast to the dramatic reorganization implied between such Rodinia configurations and the subsequent assembly of Gondwana" (p. 445). This is consistent with the compilation of O'Neill et al. (2013) who found low plate motion velocities through Early and Middle Mesoproterozoic time, although a rapid increase in plate velocity was noted for Late Mesoproterozoic time. On the basis of an independent compilation of paleomagnetic data, Piper (2013) identified the 1.7–1.25 Ga time period as a single-lid episode. Piper (2013) further inferred from paleomagnetic evidence that the transition to modern plate tectonics began ~1.1 Ga. These conclusions are controversial; for example, Pisarevsky et al. (2014) argued that Nuna/Columbia assembled by 1600 Ma and broke up at 1400 Ma. Meert and Santosh (2017) noted that "... despite the exponential increase in available [paleomagnetic] data, knowledge of the assembly, duration, and breakup history of the supercontinent are contentious." Clearly, more paleomagnetic work is needed to resolve this controversy.

It should be noted that the interpretation that the Mesoproterozoic was a protracted single-lid

episode is controversial. Most geoscientists still believe that plate tectonics was operative during the Mesoproterozoic (e.g., Condie et al., 2021).

It is very important to emphasize that the change from single-lid to plate tectonics did not happen instantaneously but probably took tens to hundreds of millions of years. Once necessary conditions of lithospheric density and strength were established, the single lid must be ruptured to form the first subduction zone and the second plate. Gerya et al. (2015) suggest that a large mantle plume head did this by a process known as "Plume-induced subduction initiation." This first rupture provides a mechanism for other fragments of oceanic lithosphere to collapse by a variety of other subduction initiation mechanisms summarized by Stern and Gerya (2018), leading over time to the establishment of a global plate mosaic. How long would it take to establish a global plate network, once the process of disrupting the Mesoproterozoic single lid began? Below we use insights about Cenozoic subduction initiation processes to address this question.

Trench lengthening rates after subduction initiation along a pre-existing lithospheric weakness zone can be estimated for modern plate tectonics based on natural observations and thermomechanical models (Zhou et al., 2018, 2020); these vary from ~100 to ~600 km/Myr (100–600 mm/y). We can use this rate to calculate about how long it would take to expand from a single subduction initiation point to a global plate network with ~55,000 km of convergent plate margins, assuming a constant "infection rate" of 100–600 km/Myr; this would take from 92 to 550 Myr to accomplish. This is notably faster than 1 Gyr proposed by Bercovici and Ricard (2014) for establishing the global plate mosaic from an initially homogeneous lid (i.e., with no initial weaknesses). Indeed, the presence of localized weaknesses (proto-plate boundaries) within the Mesoproterozoic lid is expected due to the complex previous geodynamic history that likely included multiple regional/global lid activation and recycling episodes.

There is also no reason to expect a constant infection rate, it is more likely that, once subduction and new plate formation started, the “subduction infection rate” changed with time; it is also possible that subduction initiation began at more than one site. The bottom line is that we now have an idea of how the single-lid tectonic regime was ruptured in Neoproterozoic time to form the first self-sustaining subduction zone and the second plate, but we do not know where or precisely when. We do not know how this 2-plate tectonic regime grew into a global plate mosaic, but it must have been by infecting the remaining single lid, by both exploiting pre-existing lithospheric weaknesses and by creating new ones (e.g. STEP faults, Munch et al., 2020) that later collapsed to form new subduction zones and plates. We do not know how rapidly this occurred, but the transformation of the Mesoproterozoic single lid into the modern global plate mosaic must have taken a significant fraction of Neoproterozoic time. Further stimulating effects can be expected from the enhanced delivery of sediments into trenches after glaciations that lubricated and accelerated global plate tectonics (Sobolev and Brown, 2019).

6. How the Neoproterozoic transition from single-lid to plate tectonics stimulated biological evolution

In this section, we explore the possibility that accelerated biological evolution in Neoproterozoic time was mostly caused by a prolonged transition from the Mesoproterozoic single-lid tectonic regime to the Phanerozoic plate tectonic regime. We build on biogeodynamic considerations outlined earlier to identify five processes that were likely involved: (1) increased nutrient supply; (2) increased oxygenation of atmosphere and ocean during a Neoproterozoic Oxygenation Event (NOE); (3) climate amelioration; (4) increased rate of habitat formation and

destruction; and (5) moderate, sustained pressure from environmental change. (1), (2), and (3) are related. It should be noted that biogeographic principles outlined above are mostly for terrestrial evolution, whereas pre-mid Paleozoic evolution mostly occurred in a shallow marine setting; nevertheless, the basic insights are likely to apply for both environments. These five considerations are each explored further below and graphically summarized in Fig. 7.

Nutrient supply is essential for life, including several elements (such as C, N, Fe, and P) (Zerkle, 2018). Phosphorus is especially important because it is a globally limiting nutrient and plays a unique role in marine biogeochemistry and ecology, hence evolution. Researchers agree that the Mesoproterozoic biosphere was significantly less productive than today. Triple oxygen isotope results ($\Delta^{17}\text{O}$) for 1.4Ga sedimentary sulfates from the Sibley basin (Ontario, Canada) were interpreted to indicate that gross primary productivity was between about 6% and 41% of modern marine productivity (Crockford et al., 2018). A greatly enhanced supply of inorganic nutrients such as P in the Neoproterozoic is suggested by the appearance of sedimentary phosphorite deposits in Ediacaran time (Laakso et al., 2020). Because P is derived from weathering of continental crust and delivered to the ocean by rivers (Fölmi, 1996), this suggests that enhanced erosion and weathering was responsible. Uplift and orogeny at convergent plate boundaries associated with the transition to modern-style plate tectonics would have caused enhanced erosion and P delivery to the oceans. The Neoproterozoic, especially the Cryogenian and the Ediacaran, is recognized as an important time of juvenile crust formation at intra-oceanic arcs such as the Arabian–Nubian Shield (ANS). The ANS reflected the formation of new subduction zones, closing the Mozambique Ocean and leading to Ediacaran collision between E and W Gondwana fragments to form the supercontinent Greater Gondwana or Pannotia; this

prolonged orogenic cycle is often called the Pan-African event (Kröner and Stern, 2004). Pan-African uplift happened during the Snowball Earth glaciation, so erosion of orogenic highlands would have been especially intense. Ediacaran collision to form the East African Orogen produced a collisional mountain range that was >8000km long and generally >1000km wide, which Squire et al. (2006) called the Transgondwanan Supermountains. More than $100 \times 10^6 \text{ km}^3$ of detrital sediment, eroded from this uplift, was deposited in the flanking Gondwana Super-fan System over the next 250Myrs. This incredible volume is enough to cover all 50 US states with $\sim 10\text{km}$ of sediment,

reflecting the enormous erosion of a gigantic mountain range! The huge Transgondwanan Supermountains, which straddled the equator, must have set up a powerful monsoon system that further promoted erosion, chemical weathering, and delivery of key trace elements to the ocean.

Support for the interpretation of unprecedented uplift, erosion, and weathering in Ediacaran time comes from the seawater Sr curve. $^{87}\text{Sr}/^{86}\text{Sr}$ of marine carbonates (seawater proxies) increased rapidly through Neoproterozoic time from near mantle-like values of ~ 0.7055 in the Tonian to the highest values in Earth history of ~ 0.7095 in early Paleozoic time (Fig. 6;

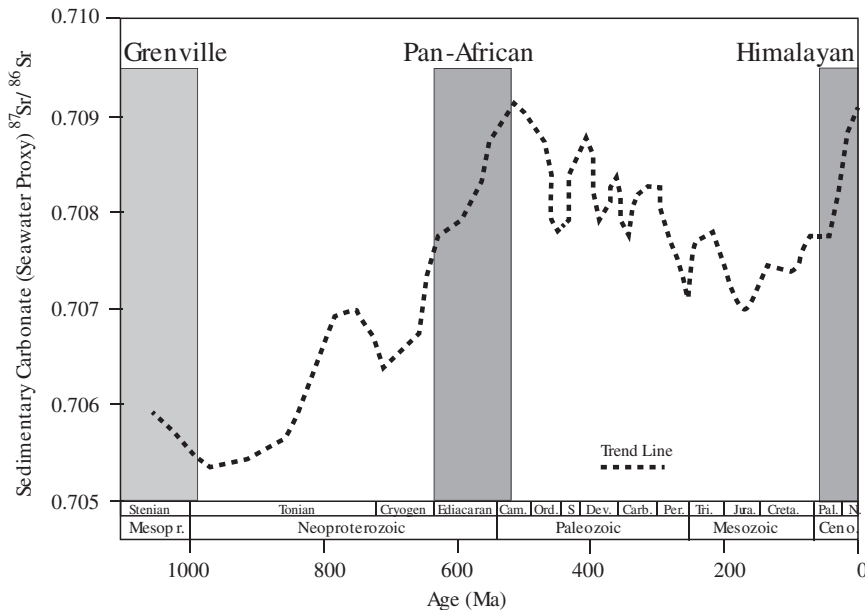


FIG. 6 Sr isotope composition of marine carbonates 0–1100Ma, simplified after Godderris et al. (2017). Marine carbonates capture $^{87}\text{Sr}/^{86}\text{Sr}$ that they form from and so provide a record of seawater Sr isotopic compositions with time. Low $^{87}\text{Sr}/^{86}\text{Sr}$ indicates that Sr input to the ocean is dominated by mantle sources (mantle $^{87}\text{Sr}/^{86}\text{Sr} \sim 0.703$), especially alteration of oceanic basalts. High $^{87}\text{Sr}/^{86}\text{Sr}$ indicates dominance of inputs from old continental crust. Note the comparably strong increases associated with Pan-African and the ongoing Himalayan continental collision events, reflecting greatly increased inputs of radiogenic Sr to the global ocean. Note also that the Grenville orogeny had no comparable effect on seawater Sr isotopic compositions, indicating that it was fundamentally different. The marine carbonate $^{87}\text{Sr}/^{86}\text{Sr}$ record for Mesoproterozoic time and earlier is not as well defined as for later times but major excursions are not reported. Further research is needed to extend this curve back in time. Abbreviations: *Cam.* = Cambrian; *Carb.* = Carboniferous; *Ceno.* = Cenozoic; *Creta.* = Cretaceous; *Cryogen* = Cryogenian; *Dev.* = Devonian; *Jura.* = Jurassic; *Mesop.* = Mesoproterozoic; *N* = Neogene; *Ord.* = Ordovician; *Pal.* = Paleogene; *Per.* = Permian; *S* = Silurian; *Tri.* = Triassic.

Godderis et al., 2017). Increased seawater $^{87}\text{Sr}/^{86}\text{Sr}$ reflects increased flux of radiogenic Sr from the continents, principally Pan-African uplifts, including the Transgondwanan Supermountains. Such strong uplifts require continental collision and did not occur during the Mesoproterozoic single-lid episode, as shown by low marine carbonate $^{87}\text{Sr}/^{86}\text{Sr}$ throughout Mesoproterozoic time, including the $\sim 1.0\text{Ga}$ Grenville Orogeny (Cawood and Hawkesworth, 2014). The remarkable Ediacaran uplift, erosion, and weathering captured by the seawater Sr isotope curve would also have resulted in an unprecedented flux of nutrients into the oceans. The addition of P, Fe, and other nutrients from erosion and weathering of Ediacaran mountain ranges that formed as a result of Pan-African continental collisions broke the Mesoproterozoic nutrient “drought,” stimulating life, speciation, and evolution. The geologic record clearly indicates a significant increase in nutrients supplied from the continents to the oceans during Neoproterozoic time, consistent with a protracted Neoproterozoic transition from Mesoproterozoic single-lid to Phanerozoic plate tectonics.

Ocean currents and tides are important in redistributing nutrients derived from continents and both were likely affected by the Neoproterozoic tectonic transition. Whereas ocean circulation intensity for the end of the Neoproterozoic remains uncertain, preliminary estimates of tidal dissipation show a pronounced increase during this time (Davies, 2021). Periods of enhanced tidal dissipation or “super-tides” are most likely to occur in a supercontinent cycle when the supercontinent is dispersing or converging and therefore ocean basins are widening and/or narrowing (Green et al., 2018; Davies, 2021). This would be the case for the onset of modern plate tectonics.

Free oxygen in ocean and atmosphere in the Hadean Earth was insignificant but increased with time because of the appearance and proliferation of photosynthetic cyanobacteria. An

important reason why large, complex animals could not have evolved during the Mesoproterozoic is because they require more oxygen for respiration than was available. Mesoproterozoic oxygen levels are estimated to have been $\sim 1\%$ present atmospheric levels (PAL; Lyons, et al., 2014). Minimum oxygen thresholds depend on animal size, mobility, nervous system, etc., but there is general agreement that the Mesoproterozoic atmosphere and shallow ocean could not support anything more complex than a sponge and was much less than the 0.1–0.25 PAL needed to support Cambrian metazoa (Williams et al., 2019). A Neoproterozoic Oxygenation Event (NOE) is proposed based on a range of isotopic proxies, and this led to a much more oxygenated environment by Late Ediacaran time. Several explanations for the NOE have been advanced. One is that an increased supply of nutrients into the oceans stimulated phytoplankton growth, which converted CO_2 into organic matter. This was further stimulated by the evolution of new plants such as algae in late Cryogenian time (659–645 Ma; Brocks, 2018), which transformed the base of the food chain and accelerated the production of free oxygen. Another explanation is that enhanced chemical weathering of continents was responsible (Mills et al., 2014). Central to all of these explanations is that more dead cyanobacteria and algae—organic carbon—must be buried. Increased burial of organic carbon can be expected as a result of enhanced sediment supply and the formation of new rift basins and passive continental margins accompanying the transition from Mesoproterozoic single lid to a global Phanerozoic plate mosaic in Neoproterozoic time.

Climate is an important control on life. Life can exist between temperatures around the freezing of water and $\sim 120^\circ\text{C}$, but thriving complex life has a much more limited temperature tolerance. Plate tectonics and single-lid tectonics control climate differently. Plate tectonics and the supercontinent cycle control Earth’s climate

in four main ways. First, gases released from magmas can either warm or cool the planet, depending on plate tectonic setting. CO₂ emissions associated with especially mid-ocean ridge and mantle plume igneous activity encourages atmospheric warming, whereas explosive volcanism associated with convergent margins injects SO₂ into the stratosphere and causes cooling (e.g., Schmidt et al., 2012). Second, proportions of Earth's surface covered by water exert a strong control on climate, more temperate when the proportion is high and harsher when it is low. Long-term sea-level rise and fall (tectonoeustasy) mostly reflects the mean age of seafloor, which changes systematically over Wilson and Supercontinent cycles. Consequently, plate-tectonic Earth experienced systematic changes in climate, with warmer (greenhouse) climates dominating about 100 Myr after continental breakup as a new ocean is opening (Worsley and Nance, 1989). It is unknown what would control seafloor depth on single-lid Earth and thus how sea level would behave, but it is likely to have changed less than for plate tectonics. Third, weathering of silicate rocks consumes atmospheric CO₂ so mountain building—which exposes more silicate rocks—leads to atmospheric cooling (e.g., West et al., 2005). Enhanced erosion and weathering associated with plate tectonic uplifts due to rifting and orogenesis releases more nutrients like P and Fe that foster photosynthetic life which, if sufficient dead organisms and the C they contain are buried, sequester CO₂ to cool climate. Uplifts on a single-lid Earth should be lower, nutrient flux reduced, and climate affected less. Fourth, subduction removes large volumes of marine carbonate rocks and organic carbon, removing CO₂ from the near-surface and sequestering it in the mantle, leading to climate cooling (Plank and Manning, 2019). Such plate tectonic controls, modified by Milankovitch cycles operating over much shorter timescales (e.g., Bennett, 1990), are largely responsible for Earth's climate today.

It is much less clear what are the climate controls for a single-lid planet in general and for Mesoproterozoic Earth in particular. The two active single-lid planets in our Solar System have atmospheres that differ greatly in density, from 93× that of Earth's atmosphere on Venus to <1% of Earth's on Mars, but both are >95% CO₂. Carbon dioxide atmospheres are expected for actively convecting silicate bodies lacking plate tectonics, water-mediated weathering, and photosynthetic life. Such atmospheres presumably reflect volcanic hot spot inputs and a lack of ways to remove this gas. In spite of it being a protracted single-lid episode, Mesoproterozoic Earth experienced a tolerably warm climate, with no evidence for glaciation despite the Sun being ~5%–20% less luminous than today (Gough, 1981). Elevated concentrations of greenhouse gases CO₂ and methane (CH₄) in the atmosphere are likely to have kept Mesoproterozoic climate warm, with elevated atmospheric abundances of carbon dioxide thought to be most important (e.g., Pavlov et al., 2003). We are beginning to quantitatively model climate on active single-lid silicate bodies (Lenardic et al., 2016, Foley, 2019), but there is much work to be done.

Habitat formation and destruction is an integral part of plate tectonics via the Wilson and Supercontinent cycles. Ever since Darwin visited the Galapagos in 1835, scientists have appreciated the essential role that isolated habitats play in allopatric speciation. Plate tectonics makes and destroys habitats much faster and efficiently than is likely for active single-lid tectonic regimes. The pace of evolution as a function of continental fragmentation has been proposed and confirmed (Valentine and Moores, 1970; Zaffos et al., 2017); very little more needs to be said here on this point.

Moderate sustained pressure on organisms from continuous environmental change happens with plate tectonics, much less so for single-lid tectonics. Nutrient fluxes, topography, climate, and habitats change continuously but moderately

for plate tectonics. Strong tectonic–erosion coupling produces long-lived complex and variable landscape, climate, and precipitation patterns that are especially pronounced along active plate boundaries. This complexity stimulates biodiversity (Pellissier et al., 2017). Continental rifting and plate divergence are in turn capable of producing large continental shelves subjected to intense sediment and nutrient delivery from the neighboring continents. The nutrients are efficiently redistributed in shelves (including tidal processes) creating favorable environments for marine life (Pellissier et al., 2017). All these processes were increasingly stimulated by the transition to modern plate tectonics, helping cause the rapid diversification of life. Single-lid tectonics is largely incapable of exerting moderate, sustained environmental pressure, except through the action of mantle plumes—especially when they first reach the surface and form large igneous provinces (LIPs). The most dramatic climatic effect is global warming due to greenhouse-gases from LIPs. Subsequent cooling can be caused by CO₂ drawdown through weathering of LIP-related basalts. Other strong stresses on the biosphere include oceanic anoxia, ocean acidification, and toxic metal input (Ernst and Youbi, 2017).

7. Conclusions and suggestions for future research

This exploration is a first step toward a biogeodynamic understanding of how Earth's tectonic evolution affected its biologic evolution, retarding it in Mesoproterozoic time and accelerating it in Neoproterozoic and younger time. It builds on consensus about the remarkable acceleration of biological evolution in Neoproterozoic time and on more controversial ideas about Earth's tectonic evolution. The key influences of plate tectonics were to increase nutrient and oxygen supplies, ameliorate climate, and create long-lived and slowly evolving (i.e., on

timescales comparable to these of biological evolution of complex species) topography, climate, precipitation, and sediment delivery patterns by plate interactions at evolving convergent and divergent plate boundaries. Establishment of this life-stimulating tectonic style likely required ca. 100–500 Myr for a global plate tectonic mosaic to fully form. The hypothesis is ultimately based on twin assumptions: (1) that Earth's tectonic style is an emergent system; and (2) that tectonic transformations will surely be reflected in the history of life.

There is great need for future studies to test and refine or refute the hypothesis that biological evolution accelerated because Earth's tectonic style was transformed in Neoproterozoic time. We can only emphasize a few here. A pillar of the argument, that Mesoproterozoic tectonics were dominated by a single-lid tectonic style, is controversial. This needs to be tested by more paleomagnetic studies designed to determine if (A) Earth's magnetic field was a dipole during this time and (B) if older cratons moved independently (falsifying the postulated pillar) or together (supporting the pillar). It is also important to know if and when true polar wander occurred because this is expected to result from mass redistributions caused by the transition to plate tectonics. More work is needed to understand the significance of the Grenville Orogeny, which is similar in many ways to Pan-African and Himalayan collisional orogens but shows none of the plate tectonic indicators and had no significant impact on seawater ⁸⁷Sr/⁸⁶Sr and δ¹³C. More research on Tonian tectonics and environment is needed. The Tonian (1000–720 Ma) is the longest period after the Archean, encompassing 60% of Neoproterozoic time and is equivalent in duration to about half of Mesoproterozoic time, but it has received far less geologic attention than the much shorter Cryogenian and Ediacaran periods. Tonian life and tectonics differ in many ways from those of Cryogenian and Ediacaran time and more like the Mesoproterozoic. Further

How Different Tectonic Styles Influence Life Differently

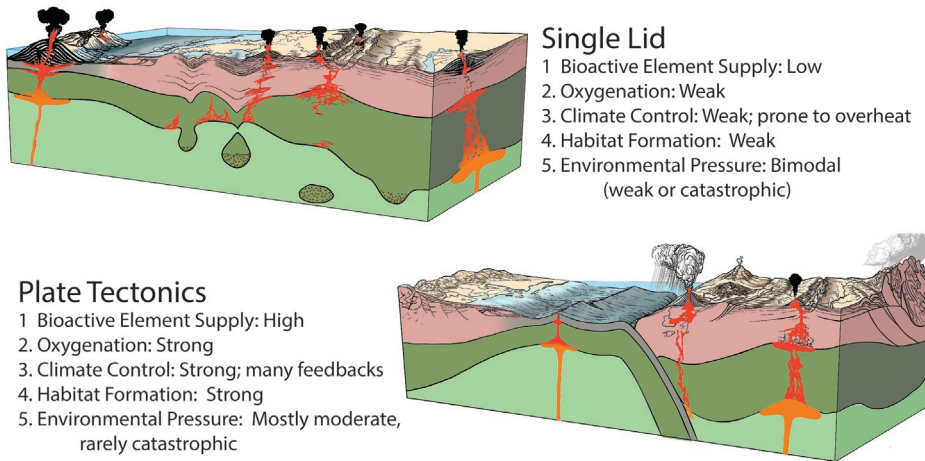


FIG. 7 Summary diagram showing how plate tectonics stimulates life and evolution, whereas a single-lid tectonic style retards life and evolution. See text for further discussion.

work is needed to refine the Mesoproterozoic $^{87}\text{Sr}/^{86}\text{Sr}$ and $\delta^{13}\text{C}$ records from marine carbonates. Further research is also needed to model how long it would take for establishing a plate tectonic global mosaic to form once physical conditions are ripe and the first subduction zone forms.

Acknowledgments

This work was supported by SNF Research Grant 200021_192296 and by ILP Task Force "Biogeodynamics of the Lithosphere." We greatly appreciate advice from Andy Knoll, a critical review by Kent Condie and comments by Jean Bedard. We also thank Clinton Crowley for making Fig. 7. This is UTD Geosciences Dept. contribution #1701.

References

- Aloy, J., 2008. Dynamics of origination and extinction in the marine fossil record. *PNAS* 105, 11536–11542.
- Ashwal, L.D., Bybee, G.M., 2017. Crustal evolution and the temporality of anorthosites. *Earth Sci. Rev.* 173, 307–330.
- Badgley, C., 2010. Tectonics, topography, and mammalian diversity. *Ecography* 3, 220–231.
- Bagley, J.C., Johnson, J.B., 2014. Phylogeography and biogeography of the lower Central American Neotropics: diversification between two continents and between two seas. *Biol. Rev.* 89, 767–790.
- Bédard, J.H., 2010. Parental magmas of Grenville province massif-type anorthosites, and conjectures about why massif anorthosites are restricted to the Proterozoic. *Trans. R. Soc. Edinb.* 100, 77–103.
- Bennett, K., 1990. Milankovitch cycles and their effects on species in ecological and evolutionary time. *Paleobiology* 16 (1), 11–21. <https://doi.org/10.1017/S0094837300009684>.
- Bercovici, D., Ricard, Y., 2014. Plate tectonics, damage and inheritance. *Nature* 508, 513–516.
- Bidegaray-Batista, L., Arnedo, M.A., 2011. Gone with the plate: the opening of the Western Mediterranean basin drove the diversification of ground-dweller spiders. *BMC Evol. Biol.* 11, 317.
- Bradley, D., 2011. Secular trends in the geological record and the supercontinent cycle. *Earth-Sci. Rev.* 108, 16–33.
- Braun, J., Yamato, P., 2010. Structural evolution of a three-dimensional, finite-width crustal wedge. *Tectonophysics* 484, 181–192.
- Briggs, J.C., 2003. The biogeographic and tectonic history of India. *J. Biogeogr.* 30, 381–388.
- Brocks, J.J., 2018. The transition from a cyanobacterial to algal world and the emergence of animals. *Emerg. Top. Life Sci.* <https://doi.org/10.1042/ETLS20180039>.
- Brown, M., Johnson, T., 2018. Invited centennial article: secular change in metamorphism and the onset of global plate tectonics: the. *Am. Mineral.* 103, 181–196. <https://doi.org/10.2138/am-2018-6166>.

- Brown, M., Kirkland, C.L., Johnson, T.E., 2020. Evolution of geodynamics since the Archean: significant change at the dawn of the Phanerozoic. *Geology* 48, 488–492.
- Brune, S., Williams, S.E., Müller, R.D., 2017. Potential links between continental rifting, CO₂ degassing and climate change through time. *Nat. Geosci.* 10, 941.
- Butterfield, N.J., 2015. The neoproterozoic. *Curr. Biol.* 25, R859–R863.
- Cawood, P.A., Hawkesworth, C.J., 2014. Earth's middle age. *Geology* 42, 503–506.
- Chowdhury, P., Gerya, T., Chakraborty, S., 2017. Emergence of silicic continents as the lower crust peels off on a hot plate-tectonic earth. *Nat. Geosci.* 10, 698–703.
- Cohen, P.A., Macdonald, F.A., 2015. The Proterozoic record of eukaryotes. *Paleobiology* 41, 610–632.
- Condie, K.C., 2014. How to make a continent: thirty-five years of TTG research. In: Dilek, Y., Furnes, H. (Eds.), *Evolution of Archean Crust and Early Life, Modern Approaches in Solid Earth Sciences 7*. Springer Science +Business Media Dordrecht, pp. 179–193.
- Condie, K.C., 2018. A planet in transition: the onset of plate tectonics on Earth between 3 and 2 Ga? *Geosci. Front.* 9, 51–60.
- Condie, K.C., Pisarevsky, S.A., Puetz, S.J., 2021. LIPs, orogens, and supercontinents. *Gondwana Res.* 96, 105–121.
- Crameri, F., Tackley, P.J., Meilick, I., Gerya, T.V., Kaus, B.J.P., 2012. A free plate surface and weak oceanic crust produce single-sided subduction on earth. *Geophys. Res. Lett.* 39, L03306.
- Crockford, P.W., Hayles, J.A., Bao, H., Planavsky, N.J., Bekker, A., Fralick, P.W., Halverson, G.P., Bui, T.H., Peng, Y., Wing, B.A., 2018. Triple oxygen isotope evidence for limited mid-Proterozoic primary productivity. *Nature* 559, 613–616.
- Dall'Agnol, R., Frost, C.D., Råmo, O.T., 2012. Editorial: IGCP project 510 "A-type granites and related rocks through time": project vita, results, and contribution to granite research. *Lithos* 151, 1–16.
- Davaille, A., Smrekar, S.E., Tomlinson, S., 2017. Experimental and observational evidence for plume-induced subduction on Venus. *Nat. Geosci.* 10, 349–355.
- Davies, H.S., 2021. Is the Earth Currently in a Global Tidal Maximum? 500 ma of Coupled Tectonic and Tidal Modelling (Ph.D. thesis). University of Lisbon (178 pp.).
- Davies, R.G., Orme, C.D.L., Storch, D., Olson, V.A., Thomas, G.H., Ross, S.G., Ding, T.S., Rasmussen, P.C., Bennett, P.M., Owens, I.P., Blackburn, T.M., 2007. Topography, energy and the global distribution of bird species richness. *Proc. R. Soc. B Biol. Sci.* 274, 1189–1197.
- Defossez, E., Pitteloud, C., Descombes, P., Glauser, G., Allard, P.-M., Walker, T.W.N., Fernandez-Conradi, P., Wolfender, J.-L., Pellissier, L., Rasmann, S., 2021. Spatial and evolutionary predictability of phytochemical diversity. *PNAS* 118, e2013344118. <https://doi.org/10.1073/pnas.2013344118>.
- Dehant, V., Debaille, V., Dobos, V., Gaillard, F., Gillmann, C., Goderis, S., Grenfell, J.L., Höning, D., Javaux, E.J., Karatekin, Ö., Morbidelli, A., 2019. Geoscience for understanding habitability in the solar system and beyond. *Space Sci. Rev.* 215 (6), 1–48.
- Descombes, P., Gaboriau, T., Albouy, C., Heine, C., Leprieux, F., Pellissier, L., 2018. Linking species diversification to palaeo-environmental changes: a process-based modelling approach. *Glob. Ecol. Biogeogr.* 27, 233–244.
- Donnadieu, Y., Godderis, Y., Pierrehumbert, R., Dromart, G., Fluteau, F., Jacob, R., 2006. A GEOCLIM simulation of climatic and biogeochemical consequences of Pangea breakup. *Geochem. Geophys. Geosyst.* 7, Q11019.
- Donnadieu, Y., Godd  ris, Y., Bouttes, N., 2009. Exploring the climatic impact of the continental vegetation on the Mesozoic atmospheric CO₂ and climate history. *Clim. Past* 5, 85–96.
- Dos Rios, M., Thawomattana, Y., Angelis, K., Telford, M.J., Donoghue, P.C.J., Yang, Z., 2015. Uncertainty in the timing of origin of animals and the limits of precision in molecular timescales. *Curr. Biol.* 25, 2939–2950.
- Ernst, R.E., Youbi, N., 2017. How large igneous provinces affect global climate, sometimes cause mass extinctions, and represent natural markers in the geological record. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 478, 30–52.
- Erwin, H., Laflamme, M., Tweedt, S.M., Sperling, E.A., Pisani, D., Peterson, K.J., 2011. The Cambrian conundrum: early divergence and later ecological success in the early history of animals. *Science* 334, 1091–1097. <https://doi.org/10.1126/science.1206375>.
- Evans, D.A.D., Mitchell, R.N., 2011. Assembly and breakup of the core of the paleoproterozoic-mesoproterozoic supercontinent nuna. *Geology* 11, 443–446.
- Fischer, R., Gerya, T., 2016a. Early earth plume-lid tectonics: a high-resolution 3D numerical modelling approach. *J. Geodyn.* 100, 198–214.
- Fischer, R., Gerya, T., 2016b. Regimes of subduction and lithospheric dynamics in the Precambrian: 3D thermomechanical modeling. *Gondwana Res.* 37, 53–70.
- Foley, B.J., 2019. Habitability of earth-like stagnant lid planets: climate evolution and recovery from snowball states. *Astrophys. J.* 875, 72. 20 pp. <https://doi.org/10.3847/1538-4357/ab0f31>.
- F  lmi, K.B., 1996. The phosphorus cycle, phosphogenesis and marine phosphate-rich deposits. *Earth Sci. Rev.* 40, 55–124.
- Gerya, T.V., Connolly, J.A.D., Yuen, D.A., 2008. Why is terrestrial subduction one-sided? *Geology* 36 (1), 43–46.
- Gerya, T., Stern, R.J., Baes, M., Sobolev, S., Whattam, S., 2015. Plume-induced subduction initiation triggered plate tectonics on earth. *Nature* 527, 221–225.
- Godd  ris, Y., Le Hir, G., Macouin, M., Donnadieu, Y., Hubert-Th  ou, L., Dera, G., Aretz, M., Fluteau, F., Li, Z.X., Halverson, G.P., 2017. Paleogeographic forcing of the strontium isotopic cycle in the neoproterozoic. *Gondwana Res.* 42, 151–162.

- Goldfarb, R.J., Bradley, D., Leach, D.L., 2010. Secular variation in economic geology. *Econ. Geol.* 105, 459–465.
- Gotelli, N.J., et al., 2009. Patterns and causes of species richness: a general simulation model for macroecology. *Ecol. Lett.* 12, 873–886. <https://doi.org/10.1111/j.1461-0248.2009.01353.x>.
- Gough, D.O., 1981. Solar interior structure and luminosity variations. *Sol. Phys.* 74, 21–34.
- Green, J.A.M., Molloy, J.L., Davies, H.S., Duarte, J.C., 2018. Is there a tectonically driven supertidal cycle? *Geophys. Res. Lett.* 45, 3568–3576. <https://doi.org/10.1002/2017GL076695>.
- Gulcher, A.J.P., Gerya, T.V., Montesi, L.G.J., Munch, J., 2020. Corona structures driven by plume-lithosphere interactions and evidence for ongoing plume activity on Venus. *Nat. Geosci.* 13, 547–554.
- Hagen, O., Onstein, R.E., Flück, B., Fopp, F., Hartig, F., Pontarp, M., Albouy, C., Luo, A., Boschman, L., Cabral, J.-S., Xing, Y., Wang, Z., Rangel, T.F., Scotese, C., Pellissier, L., 2020. GEN3SIS: an engine for simulating eco-evolutionary processes in the context of plate tectonics and deep-time climate variations. In: 22nd EGU General Assembly, Abstract 20627.
- Harris, L.B., Bédard, J.H., 2015. Interactions between continent-like ‘drift’, rifting and mantle flow on Venus: gravity interpretations and earth analogues. *Geol. Soc. Lond. Spec. Publ.* 401 (1), 327–356.
- Holland, H.D., 2006. The oxygenation of the atmosphere and oceans. *Philos. Trans. R. Soc. B* 361, 903–915.
- Hoorn, C., Wesselingh, F.P., Ter Steege, H., Bermudez, M.A., Mora, A., Sevink, J., Sanmartín, I., Sanchez-Meseguer, A., Anderson, C.L., Figueiredo, J.P., Jaramillo, C., 2010. Amazonia through time: Andean uplift, climate change, landscape evolution, and biodiversity. *Science* 330 (6006), 927–931.
- Johnson, T.E., Brown, M., Kaus, B.J.P., Van Tongeren, J.A., 2014. Delamination and recycling of Archaean crust caused by gravitational instabilities. *Nat. Geosci.* 7 (1), 47–52.
- Keith, D.A., Rodríguez, J.P., Rodríguez-Clark, K.M., Nicholson, E., Aapala, K., Alonso, A., Asmussen, M., Bachman, S., Basset, A., Barrow, E.G., Benson, J.S., 2013. Scientific foundations for an IUCN Red List of Ecosystems. *PLoS One* 8 (5), e62111.
- Kendall, D.G., 1949. Stochastic processes and population growth. *J. R. Stat. Soc. B (Methodol.)* 11, 230–264.
- Knoll, A., 2014. Paleobiological perspectives on early eukaryotic evolution. *Cold Spring Harb. Perspect. Biol.* 14 (6), a016121.
- Knoll, A.H., Nowak, M.A., 2017. The timetable of evolution. *Sci. Adv.* 3, e1603076.
- Kröner, A., Stern, R.J., 2004. Pan-African orogeny. In: *Encyclopedia of Geology*. vol. 1. Elsevier, pp. 1–14.
- Laakso, T.A., Sperling, E.A., Johnston, D.T., Knoll, A.H., 2020. Ediacaran reorganization of the marine phosphorus cycle. *Proc. Natl. Acad. Sci.* 117, 11961–11967.
- Latham, R.E., Ricklefs, R.E., 1993. Global patterns of tree species richness in moist forests: energy-diversity theory does not account for variation in species richness. *Oikos* 67, 325–333.
- Lavergne, S., Hampe, A., Arroyo, J., 2013. In and out of Africa: how did the Strait of Gibraltar affect plant species migration and local diversification? *J. Biogeogr.* 40, 24–36.
- Lenardic, A., Jellinek, A., Foley, B., O’Neill, C., Moore, W., 2016. Climate-tectonic coupling: variations in the mean, variations about the mean, and variations in mode. *J. Geophys. Res. Planets* 121, 1831–1864.
- Leprieur, F., Descombes, P., Gaboriau, T., Cowman, P.F., Parravicini, V., Kulbicki, M., Bellwood, D.R., Pellissier, L., 2016. Plate tectonics drive tropical reef biodiversity dynamics. *Nat. Commun.* 7, 11461.
- Lyons, T.W., Reinhard, C.T., Planavsky, N.J., 2014. The rise of oxygen in Earth’s early ocean and atmosphere. *Nature* 506, 307–315.
- Magri, D., Vendramin, G.G., Comps, B., Dupanloup, I., Geburek, T., Gömöry, D., et al., 2006. A new scenario for the Quaternary history of European beech populations: palaeobotanical evidence and genetic consequences. *New Phytol.* 171, 199–221.
- Marshall, C., 2017. Five palaeobiological laws needed to understand the evolution of the living biota. *Nat. Ecol. Evol.* 1, 0165.
- Meert, J.G., Santosh, M., 2017. The Columbia supercontinent revisited. *Gondwana Res.* 50, 67–83.
- Mills, B., Lenton, T.M., Watson, A.J., 2014. Proterozoic oxygen rise linked to shifting balance between seafloor and terrestrial weathering. *Proc. Natl. Acad. Sci. U. S. A.* 111, 9073–9078.
- Mittelbach, G.G., et al., 2007. Evolution and the latitudinal diversity gradient: speciation, extinction and biogeography. *Ecol. Lett.* 10, 315–331. <https://doi.org/10.1111/j.1461-0248.2007.01020.x>.
- Mukherjee, I., Large, R.R., Corkrey, R., Danyushevsky, L.V., 2018. The Boring Billion, a slingshot for complex life on Earth. *Sci. Rep.* 8, 7.
- Munch, J., Gerya, T., Ueda, K., 2020. Oceanic crust recycling controlled by weakening at slab edges. *Nat. Commun.* 11, 2009.
- Namur, O., Charlier, B., Pirard, C., Hermann, J., Liégeois, J.-P., Auwera, J.V., 2011. Anorthosite formation by plagioclase flotation in ferrobasalt and implications for the lunar crust. *Geochim. Cosmochim. Acta* 75, 4998–5018.
- Nédélec, A., Monnereau, M., Toplis, M.J., 2017. The Hadean–Archaean transition at 4 Ga: from magma trapping in the mantle to volcanic resurfacing of the Earth. *Terra Nova* 29, 218–223.

- O'Neill, C., Lenardic, A., Condie, K.C., 2013. Earth's punctuated tectonic evolution: cause and effect. In Roberts, N. M. W., van Kranendonk, M., Parman, S., Shirey, S. & Clift, P. D. (eds) *Continent Formation Through Time*. Geol. Soc. Lond., Spec. Publ. 389, 17–40.
- O'Neill, C., Roberts, N.M.W., 2018. Lid tectonics—preface. *Geosci. Front.* 9, 1–2.
- Palin, R.M., Santosh, M., Cao, W., Li, S.-S., Hernández-Uribe, D., Parsons, A., 2020. Secular metamorphic change and the onset of plate tectonics. *Earth Sci. Rev.* 207. <https://doi.org/10.1016/j.earscirev.2020.103172>.
- Pavlov, A.A., Hurtgen, M.T., Kasting, J.F., Arthur, M.A., 2003. Methane-rich proterozoic atmosphere? *Geology* 31, 87–90.
- Pellissier, L., Heine, C., Rosauer, D.F., Albouy, C., 2017. Are global hotspots of endemic richness shaped by plate tectonics? *Biol. J. Linn. Soc.* 123 (1), 247–261.
- Piper, J.D.A., 2013. A planetary perspective on earth evolution: lid tectonics before plate tectonics. *Tectonophysics* 589, 44–56.
- Pisarevsky, S.A., Elming, S.-A., Pesonen, L.J., Li, Z.-X., 2014. Mesoproterozoic paleogeography: supercontinent and beyond. *Precambrian Res.* 244, 207–225.
- Plank, T., Manning, C.E., 2019. Subducting carbon. *Nature* 574, 343–352. <https://doi.org/10.1038/s41586-019-1643-z>.
- Plumb, K.A., James, H.L., 1986. Subdivision of Precambrian time: recommendations and suggestions by the subcommittee on Precambrian stratigraphy. *Precambrian Res.* 32, 65–92.
- Pontarp, M., Bunnefeld, L., Sarmiento Cabral, J., Etienne, R.S., Fritz, S.A., Gillespie, R., Graham, C.H., Hagen, O., Hartig, F., Huang, S., Jansson, R., Maliet, O., Münkemüller, T., Pellissier, L., Rangel, T.F., Storch, D., Wiegand, T., Hurlbert, A.H., 2018. The latitudinal diversity gradient: novel understanding through mechanistic eco-evolutionary models. *Trends Ecol. Evol.* <https://doi.org/10.1016/j.tree.2018.11.009>.
- Rangel, T.F., Edwards, N.R., Holden, P.B., Diniz-Filho, J.A.F., Gosling, W.D., Coelho, M.T.P., Colwell, R.K., 2018. Modeling the ecology and evolution of biodiversity: biogeographical cradles, museums, and graves. *Science* 361 (6399), eaar5452.
- Richardson, J.E., Bakar, A.M., Tosh, J., Armstrong, K., Smedmark, J., Anderberg, A.A., Slik, F., Wilkie, P., 2014. The influence of tectonics, sea-level changes and dispersal on migration and diversification of *Isonandreae* (Sapotaceae). *Bot. J. Linn. Soc.* 174, 130–140.
- Rogers, J.J., Santosh, M., 2002. Configuration of Columbia, a mesoproterozoic supercontinent. *Gondwana Res.* 5 (1), 5–22.
- Rolf, T., Coltice, N., Tackley, P.J., 2012. Linking continental drift, plate tectonics and the thermal state of the Earth's mantle. *Earth Planet. Sci. Lett.* 351–352, 134–146.
- Rolf, T., Coltice, N., Tackley, P.J., 2014. Statistical cyclicity of the supercontinent cycle. *Geophys. Res. Lett.* 41. <https://doi.org/10.1002/2014GL059595>.
- Schluter, D., Pennell, M.W., 2017. Speciation gradients and the distribution of biodiversity. *Nature* 546 (7656), 48.
- Schmidt, A., Carslaw, K.S., Mann, G.W., Rap, A., Pringle, K.J., Spracklen, D.V., Wilson, M., Forster, P.M., 2012. Importance of tropospheric volcanic aerosol for indirect radiative forcing of climate. *Atmos. Chem. Phys.* 12, 7321–7339. <https://doi.org/10.5194/acp-12-7321-2012>.
- Silver, P.G., Behn, M.D., 2008. Intermittent plate tectonics? *Science* 319, 85–88.
- Sizova, E., Gerya, T., Brown, M., Perchuk, L.L., 2010. Subduction styles in the Precambrian: insight from numerical experiments. *Lithos* 116, 209–229.
- Sizova, E.V., Gerya, T.V., Brown, M., 2014. Contrasting styles of Phanerozoic and Precambrian continental collision. *Gondwana Res.* 25, 522–545.
- Sizova, E., Gerya, T., Stuewe, K., Brown, M., 2015. Generation of felsic crust in the Archean: a geodynamic modeling perspective. *Precambrian Res.* 271, 198–224.
- Smrekar, S.E., Davaille, A., Sotin, C., 2018. Venus Interior structure and dynamics. *Space Sci. Rev.* 214, 88. <https://doi.org/10.1007/s11214-018-0518-1>.
- Sobolev, S.V., Brown, M., 2019. Surface erosion events controlled the evolution of plate tectonics on earth. *Nature* 570, 52–57. <https://doi.org/10.1038/s41586-019-1258-4>.
- Sobolev, S.V., Sobolev, A.V., Kuzmin, D.V., Krivolutszkaya, N.A., Petrunin, A.G., Arndt, N.T., Radko, V.A., Vasiliev, Y.R., 2011. Linking mantle plumes, large igneous provinces and environmental catastrophes. *Nature* 477, 312–316.
- Squire, R.R.J., Campbell, I.H., Allen, C.M., Wilson, C.J.L., 2006. Did the transgondwanan supermountain trigger the explosive radiation of animals on earth? *Earth Planet. Sci. Lett.* 250, 116–133.
- Steeman, M.E., Hebsgaard, M.B., Fordyce, R.E., Ho, S.Y., Rabosky, D.L., Nielsen, R., Rahbek, C., Glenner, H., Sørensen, M.V., Willerslev, E., 2009. Radiation of extant cetaceans driven by restructuring of the oceans. *Syst. Biol.* 58, 573–585.
- Stein, A., Gerstner, K., Kreft, H., 2014. Environmental heterogeneity as a universal driver of species richness across taxa, biomes and spatial scales. *Ecol. Lett.* 17, 866–880.
- Stern, R.J., 2016. Is plate tectonics needed to evolve technological species on exoplanets? *Geosci. Front.* 7, 573–580.
- Stern, R.J., 2018. The evolution of plate tectonics. *Philos. Trans. R. Soc. A* 376, 20170406. <https://doi.org/10.1098/rsta.2017.0406>.
- Stern, R.J., 2020. The Mesoproterozoic single lid tectonic episode: prelude to plate tectonics. *GSA Today* 30 (12), 4–10.
- Stern, R.J., Gerya, T., 2018. Subduction initiation in nature and models: a review. *Tectonophysics* 746, 173–198.

- Stern, R.J., Gerya, T., 2021. Earth evolution, emergence, and uniformitarianism. *GSA Today* 31 (1), 32–33.
- Stern, R.J., Gerya, T., Tackley, P., 2018. Planetoid tectonics: perspectives from silicate planets, dwarf planets, large moons, and large asteroids. *Geosci. Front.* 9, 103–119.
- Thieulot, C., Steer, P., Huismans, R.S., 2014. Three-dimensional numerical simulations of crustal systems undergoing orogeny and subjected to surface processes. *Geochem. Geophys. Geosyst.* 15, 4936–4957.
- Toussaint, E., Hall, R., Monaghan, M., et al., 2014. The towering orogeny of New Guinea as a trigger for arthropod megadiversity. *Nat. Commun.* 5, 4001. <https://doi.org/10.1038/ncomms5001>.
- Ueda, K., Willett, S.D., Gerya, T., Ruh, J., 2015. Geomorphological-thermo-mechanical modeling: application to orogenic wedge dynamics. *Tectonophysics* 659, 12–30.
- Valentine, J., Moores, E., 1970. Plate-tectonic regulation of faunal diversity and sea level: a model. *Nature* 228, 657–659.
- Van Heck, H.J., Tackley, P.J., 2011. Plate tectonics on super-Earths: equally or more likely than on Earth. *Earth Planet. Sci. Res.* 310, 252–261.
- Van Keken, P.E., Hacker, B.R., Syracuse, E.M., Abers, G.A., 2011. Subduction factory: 4. Depth-dependent flux of H₂O from subducting slabs worldwide. *J. Geophys. Res.* 116 (B1), B01401.
- Van Kranendonk, M.J., 2010. Two types of Archean continental crust: plume and plate tectonics on early earth. *Am. J. Sci.* 310 (10), 1187–1209.
- Van Thienen, P., Vlaar, N.J., van den Berg, A.P., 2005. Assessment of the cooling capacity of plate tectonics and flood volcanism in the evolution of Earth, Mars and Venus. *Phys. Earth Planet. Inter.* 150, 287–315.
- West, A.J., Galy, A., Bickle, M., 2005. Tectonic and climatic controls on silicate weathering. *Earth Planet. Sci. Lett.* 235, 211–228.
- Williams, J.J., Mills, B.J.W., Lenton, T.M., 2019. A tectonically driven Ediacaran oxygenation event. *Nat. Commun.* 10, 2690. <https://doi.org/10.1038/s41467-019-10286-x>.
- Willig, M.R., Kaufman, D.M., Stevens, R.D., 2003. Latitudinal gradients of biodiversity: pattern, process, scale, and synthesis. *Annu. Rev. Ecol. Evol. Syst.* 34, 273–309. <https://doi.org/10.1146/annurev.ecolsys.34.012103.144032>.
- Worsley, T.R., Nance, D.R., 1989. Carbon redox and climate control through earth history: a speculative reconstruction. *Glob. Planet. Chang.* 1, 259–282.
- Zaffos, A., Finnegan, S., Peters, S.E., 2017. Plate tectonic regulation of biodiversity. *Proc. Natl. Acad. Sci.* 114 (22), 5653–5658. <https://doi.org/10.1073/pnas.1702297114>.
- Zerkle, A.L., 2018. Biogeodynamics: bridging the gap between surface and deep earth processes. *Philos. Trans. R. Soc. A* 376, 2017040120170401. <https://doi.org/10.1098/rsta.2017.0401>.
- Zhou, X., Li, Z.H., Gerya, T.V., Stern, R.J., Xu, Z.Q., Zhang, J.J., 2018. Subduction initiation dynamics along a transform fault control trench curvature and ophiolite ages. *Geology* 46, 607–610.
- Zhou, X., Li, Z.-H., Gerya, T., Stern, R.J., 2020. Lateral propagation-induced subduction initiation at passive continental margins controlled by preexisting lithospheric weakness. *Sci. Adv.* 6, eaaz1048.