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Is plate tectonics needed to evolve technological species on exoplanets?

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A R T I C L E I N F O

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A B S T R A C T

As we continue searching for exoplanets, we wonder if life and technological species capable of communicating with us exists on any of them. As geoscientists, we can also wonder how important is the presence or absence of plate tectonics for the evolution of technological species. This essay considers this question, focusing on tectonically active rocky (silicate) planets, like Earth, Venus, and Mars. The development of technological species on Earth provides key insights for understanding evolution on exoplanets, including the likely role that plate tectonics may play. An Earth-sized silicate planet is likely to experience several tectonic styles over its lifetime, as it cools and its lithosphere thickens, strengthens, and becomes denser. These include magma ocean, various styles of stagnant lid, and perhaps plate tectonics. Abundant liquid water favors both life and plate tectonics. Ocean is required for early evolution of diverse single-celled organisms, then colonies of cells which specialized further to form guts, appendages, and sensory organisms up to the complexity of fish (central nervous system, appendages, eyes). Large expanses of dry land also begin in the ocean, today produced above subduction zones in juvenile arcs and by their coalescence to form continents, although it is not clear that plate tectonics was required to create continental crust on Earth. Dry land of continents is required for further evolution of technological species, where modification of appendages for grasping and manipulating, and improvement of eyes and central nervous system could be perfected. These bioassets allowed intelligent creatures to examine the night sky and wonder, the beginning of abstract thinking, including religion and science. Technology arises from the exigencies of daily living such as tool-making, agriculture, clothing, and weapons, but the pace of innovation accelerates once it is allied with science. Finally, the importance of plate tectonics for developing a technological species is examined via a thought experiment using two otherwise identical planets: one with plate tectonics and the other without. A planet with oceans, continents, and plate tectonics maximizes opportunities for speciation and natural selection, whereas a similar planet without plate tectonics provides fewer such opportunities. Plate tectonics exerts environmental pressures that drive evolution without being capable of extinguishing all life. Plate tectonic processes such as the redistribution of continents, growth of mountain ranges, formation of land bridges, and opening and closing of oceans provide a continuous but moderate environmental pressure that stimulates populations to adapt and evolve. Plate tectonics may not be needed in order for life to begin, but evolution of technological species is favored on planets with oceans, continents, plate tectonics, and intermittently clear night sky.

1. Introduction

This paper addresses the question: Does plate tectonics make a difference for biological evolution; in particular, does it matter for evolving a technological species such as ourselves? This is not an easy question to answer, because the solid Earth and life on it are complex systems with complex interrelationships; still, it is a worthwhile exploration. Our understanding of the modern solid Earth is encapsulated in the theory of plate tectonics, which states that Earth's outer, strong layer – the lithosphere – is broken up into many individual, interacting plates independently moving towards, away from, and past each other at rates of ~1–10 cm/yr (Niu, 2015).

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Our understanding of biology is similarly encapsulated by the Theory of Natural Selection and Evolution, largely as articulated by Darwin (1859). The solid Earth has been shaped by the operation of plate tectonics over many millions of years whereas life has been molded by evolutionary processes operating over a comparable timespan. The question of how these two great systems interact should be considered as we search for exoplanets orbiting other stars in our galaxy and as we listen for messages from other civilizations that might exist elsewhere in the universe.

The term "technological species" should be defined. Technology includes all tools, machines, utensils, weapons, instruments, housing, clothing, communicating and transporting devices and the skills by which we produce and use them (Bain, 1937), and species is a group of organisms capable of interbreeding to produce fertile offspring. Thus "technological species" refers to an interbreeding group of organisms that depends on technology for its success. Creatures on other planets capable of communicating with us must also be technological species, if they exist.

Darwin explained the principles of biological evolution more than a century before plate tectonic theory was articulated in the 1960's, but once the latter theory was established, geoscientists began thinking about how plate tectonics affected evolution. A key paper by Valentine and Moores (1970) examined how continental and oceanic reconfigurations affected diversity through Phanerozoic time, using marine invertebrates living on shallow continental shelves as examples. Building on Darwin's insight that natural selection and thus faunal diversity was ultimately regulated by environmental stability, nutrient supply, and provinciality, they showed how recombinations and redivisions of land and marine realms via plate tectonics affected invertebrate evolution. More recently, Worsley et al. (1984) articulated the supercontinent cycle, whereby plate tectonic movements continuously reconfigure oceanic and continental realms over several hundred million years. These reconfigurations not only produce different geographic realms, they also control a wide range of environmental factors that directly impact evolution, including sealevel and climate.

It is useful to revisit the issue of how plate tectonics affects evolution, for two reasons. First, the question of when and how plate tectonics started on Earth is receiving increased attention (Korenaga, 2013) and its eventual resolution will surely impact our understanding of how life evolved. At present there is no consensus on when plate tectonics began on Earth; the right half of Fig. 1 summarizes when 10 different studies infer that plate tectonics began; these range from ~0.85 Ma to >4.2 Ga. Neither is there any consensus about what Earth's tectonic style was before this signal event, or how the transition to plate tectonics was accomplished. There could have been brief episodes and locations of plate tectonic-like behavior before the modern episode of continuous, global plate tectonics was established. Probably the pre-plate tectonic Earth was characterized by some sort of unstable stagnant lid, like the present tectonic style of Venus (Solomatov and Moresi, 1996). We cannot yet even be sure that plate tectonics started after life began (so that the change from stagnant lid to plate tectonics could have affected evolution). Life on Earth began sometime before 3.8 Ga ago (Mojzis et al., 1996), and 7 out of 10 estimates for when plate tectonics began are younger than this (Fig. 1). On the other hand, all workers agree that plate tectonics began simultaneous with or before the evolution of multicellular animals (metazoa) in Neoproterozoic (1000–542 Ma) time (Morris, 1993) culminating in the Cambrian "explosion", when essentially all animal phyla first appeared (Marshall, 2006). We want to know if and how plate tectonics affected this remarkable evolution, did it advance or retard it?

The second reason for exploring how plate tectonics affects life is because of the accelerating search for extraterrestrial intelligence (SETI; http://www.seti.org/). Earth is the only planet we know that has life and is also the only planet with a technological species and plate tectonics, is this cause and effect or coincidence? Are exoplanets with plate tectonics and life more likely to evolve technological species than planets with life but no plate tectonics? Webb (2002) argued that there should be many planets with technologically-capable life, able and interested to send out radio messages, why have we apparently not received any? We are finding more and more planets orbiting other stars, and some of these could have life. According to a November 2015 look at http://exoplanets.org/, 1642 total confirmed planets have been discovered in our galaxy. Only a fraction of these are likely to be rocky planets or moons, which are the only ones with any potential for plate tectonic behavior, and only a fraction of these bodies orbit in the "habitable zone" where liquid water can exist and life is possible (Kasting et al., 1993).

It is also important to understand that life must begin and evolve most of its complexity in liquid but that technologic species is only likely to evolve on dry land, where appendages adapted for running and climbing can evolve to manipulating and building. Intellectual development is also favored on dry land, because that is the vantage point from which the great mystery – the universe revealed by the night sky – can be seen. Even if a technological species could somehow evolve in the ocean of an exoplanet, the night sky would be difficult for such creatures to wonder about, study, and eventually interrogate, as humans have for thousands of years. Technological species capable to communicate with us are only likely to have evolved on an exoplanet with both oceans, continents, and a reasonably clear night sky.

Considerations of requirements for life – technological or primitive – on exoplanets rarely present the presence or absence of plate tectonics as a critical consideration (e.g., McKay, 2014). The question can be restated in terms of the Drake Equation (the probabilistic argument used to estimate the number of active, communicative extraterrestrial civilizations in our galaxy): does the presence or absence of plate tectonics affect either or both of two variables in the Drake Equation (Brownlee and Ward, 2003): f_l (the fraction of planets that could support life that actually develop life) and f_i (the fraction of planets with life that go on to develop intelligent life and civilizations)?

2. Tectonic styles of silicate planets

Before we consider how plate tectonics affects evolution, we must appreciate what a remarkable mode of planetary convection this is. We can do this by exploring what tectonic styles a silicate planet might experience over its lifetime. Silicate planets start hot due to intense early heating by accretion, differentiation, impacts, and radioactivity. Hot young planets slowly cool with time. This slow cooling is reflected in slowly thickening lithosphere (thermal boundary layer of Anderson, 1995). Lithospheric thickness is determined by the depth of the 1200–1300 °C isotherm, below which hot, weak peridotite of the asthenosphere is found, and this isotherm would have deepened as Earth cooled. As a result of cooling and progressive lithospheric thickening, a silicate planet might experience several magmatotectonic styles (Fig. 2), among which plate tectonics is only one of the several possible styles. The sequence of planetary tectonic styles shown in Fig. 2 are just suggestions, consistent with constraints from other planets and moons: what we reconstruct for the lunar crust (Nemchin et al., 2009), what is understood for Jupiter's moon Io (Moore and Webb, 2013), likely delamination modes of Venus and Earth (Solomatov and Moresi, 2012), and, of course, Earth's present tectonic style. A just-accreted planet likely had a magma ocean (Elkins-Tanton, 2008), although this phase might be very brief.

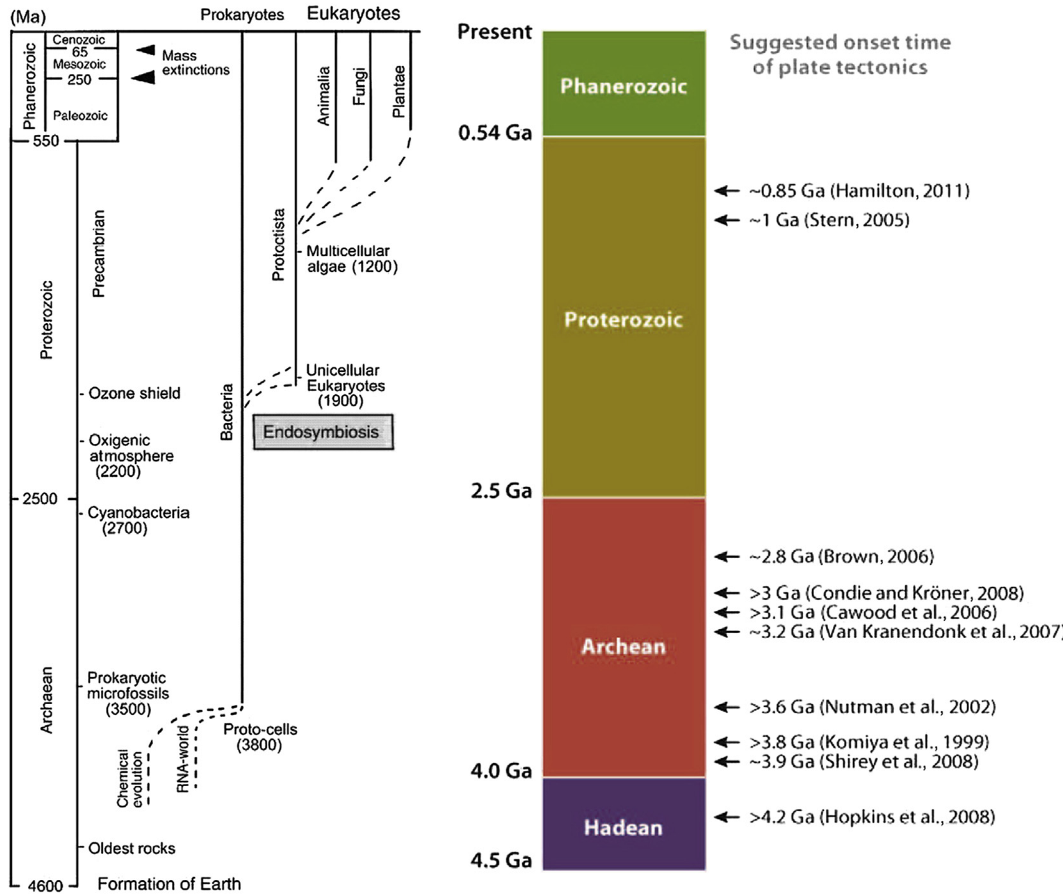

Figure 1. Geological time scale with key events in the history of life, from the formation of the Earth to the present. All five kingdoms of organisms are included (Bacteria, Protoctista, Animalia, Fungi, Plantae). Ma: millions of years (Kutschera and Niklas, 2004). Right: Geologic times cale and suggestions in the peer-reviewed literature for the onset time of plate tectonics. Suggestions shown here merely demonstrate the diversity of opinions published in the past decade or so and are not meant to be a comprehensive compilation of recent literature (Korenaga, 2013).

Shallow magma ocean might exist for only a few million years before crust forms to provide a solitary planetary surface.

After the early magma ocean stage, there are only two likely tectonic modes for a silicate planet: plate tectonics and stagnant lid tectonics. Stagnant lid tectonics basically is where the entire lithosphere of the planet is a single, globe-encircling plate. There is a wide range of expected stagnant lid behaviors, from cold and strong (such as the lunar lithosphere today) or it can be hot and weak (like the modern Venusian lithosphere) (Reese et al., 1999). The middle three stages in Fig. 2 are variants of "stagnant lid" tectonics. Earth's "boring billion", 1.7 to 0.75 Ga, was a time of environmental, evolutionary, and lithospheric stability that probably represents a protracted episode of stagnant lid tectonics (Roberts, 2013). Stagnant lid episodes on Earth before plate tectonics began probably were characterized by various styles of lithospheric behavior, perhaps with tracts of cold, strong cratonic lithosphere distributed among tracts of hot, weak oceanic lithosphere. Alternatively, recent numerical experiments suggest an opposite picture (Sizova et al., 2015): cold old slowly spreading oceans and hot weak internally deforming continents with thin to non-existing lithosphere.

Stagnant lid tectonics can range widely from unstable to stable. This sequence corresponds to increasing lithospheric thickness, which to a first approximation increases with time. A very unstable lid formed after the Early Hadean magma ocean began to crust over (Elkins-Tanton, 2008). This crust thickened and evolved with time to an unstable style of stagnant lid tectonics known as "heat pipe" (Moore and Webb, 2013). Heat pipe stagnant lid is based on observations of Jupiter's innermost satellite Io, which is heated by tidal flexing as it orbits the giant planet. Heat pipes are conduits that allow magma to flow up from the base of the crust (there is essentially no mantle lithosphere), accompanied by subsidence of cold intervening crust (Moore and Webb, 2013). Such a scenario is likely to have characterized Earth's early Hadean and to have been experienced by all large silicate bodies after magma ocean phase (Fig. 2). As this primitive volcanic crust thickened, massive basalt accumulation may have been thick enough or have been dragged down deep enough (~40 km) to form dense eclogite (O'Rourke and Korenaga, 2012), which likely would have formed dense Rayleigh–Taylor "drips" (Fig. 2). As cooling continued, mantle lithosphere began to grow at the base of the primitive crust. Stronger lithosphere required a larger scale of delamination so that convective drips and regions of delamination broaden, flanked by broadening regions of mantle upwellings or plumes. Also as the lithosphere thickened, larger mantle upwellings would be required to rupture the lithosphere to allow magmas to erupt. As the planet continued to cool, lithospheric thickening continued, accompanied by increasingly larger-scale lithospheric delamination. This is a Venusian-like stagnant lid, dominated by many active mantle plumes (manifested as coronae and arachnoids; Gerya, 2014) and periodic (300–500 Ma) volcanic resurfacings (Solomatov and Moresi, 1996; Hansen et al., 1999). Foundering of drips and slabs would likely be accompanied by abundant igneous activity and deformation, like Venus today (Solomatov and Moresi, 1996; Gerya

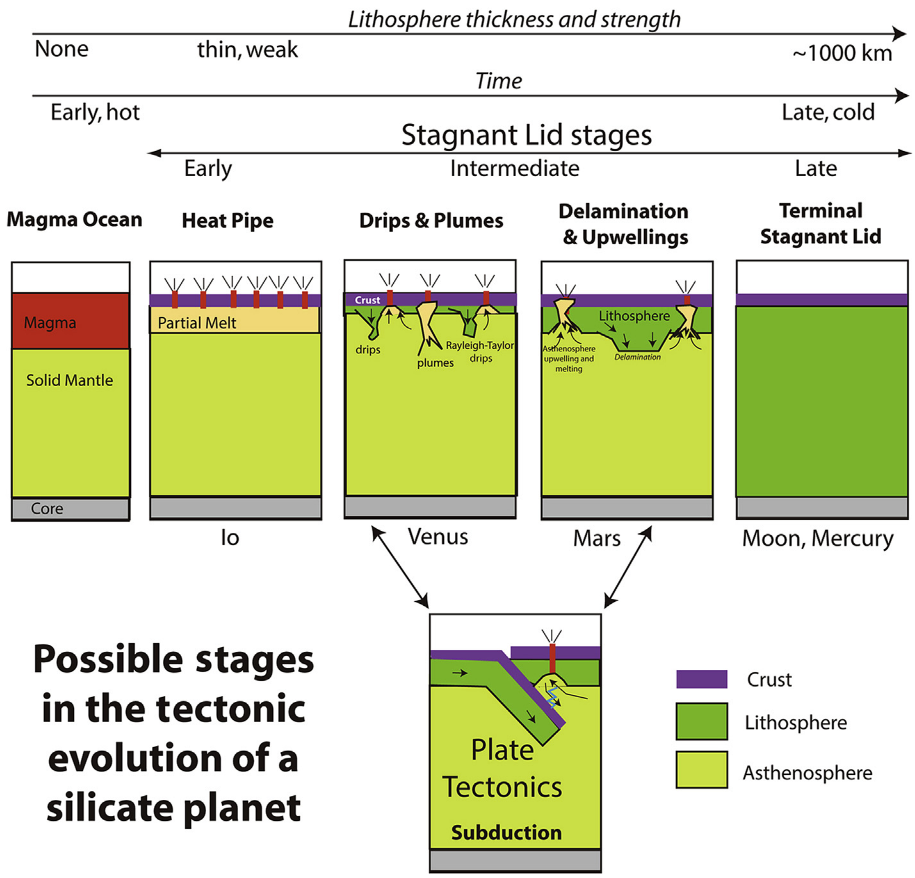

Figure 2. Possible evolution of magmatotectonic styles for a large silicate body, using the large silicate bodies in our Solar System as examples. Note that plate tectonics requires certain conditions of lithospheric strength and density to be possible. Arrows between "Plate Tectonics" and intermediate "Stagnant Lid" are intended to show that changes in the tectonic regime of a silicate planet between the two types of stagnant lid and plate tectonics are possible (Sleep, 2000; Weller and Lenardic, 2012), but that transitions back and forth from "Heat Pipe" and "Terminal Stagnant Lid" are not expected.

et al., 2015). At this stage of lithosphere thickening, plate tectonics would become possible but would not be inevitable. Further planetary cooling would lead to the present tectonic style of Mars, which has an almost completely stabilized stagnant lid. Here, a few mantle plumes continue to transfer a modicum of mass and energy from the interior to the surface; a single upwelling mantle plume, pouring lava out at the same sites for hundreds of millions of years, produced the immense Tharsis volcanoes (Zuber, 2001). When these last few mantle plumes are extinguished, the tectonic style transitions to the final stage of lid, typified by Mercury or Earth's moon. These have ultra-thick, ultra-stable lithospheres, which in the Moon's case has experienced no igneous activity for 2 Ga (Hiesinger and Head, 2006). Thus the spectrum of stagnant lid from heat pipe to ultra-stable encompasses the evolution of a planet from vigorous infancy to tectonomagmatic death.

Plate tectonics we understand very well from studying Earth. Plates are fragments of lithosphere, and lithosphere is the strong outer 100–200 km of the Earth. Lithosphere includes crust, either oceanic or continental. Plate tectonics occurs when the lithosphere is fragmented, stagnant lid when it is not. Some researchers conclude that plate tectonics should be common on rocky exoplanets (Valencia et al., 2007; Van Heck and Tackley, 2011) and others disagree (O'Neill et al., 2007). This controversy is not addressed here; instead we address the question: should we expect any differences in the complexity of life on exoplanets between those with and without plate tectonics? Given otherwise similar and suitable planetary environments, does the presence or absence of plate tectonics on an exoplanet have any affect on whether or not intelligent life is likely to evolve there?

3. Life, oceans, and continents

We do not yet understand how life began on Earth, but there is no doubt that especially its early development occurred in the ocean. The beginning of life as we know it must have involved carbon-rich molecules in a "primordial soup", an idea that was first advanced by Oparin (1938). The early Earth probably had an atmosphere dominated by carbon dioxide and methane (CO_2 and CH_3), with negligible free oxygen (O_2). Ocean was key for early life and evolution (Fig. 3). Life on Earth may have begun around hydrothermal vents (Martin et al., 2008) or it may have been introduced from outer space (Panspermia; Line, 2007). Regardless of how life originated, aqueous environments were essential for the simple, single-celled organisms that existed early in Earth history, because in this medium cytoplasm needs only a weak container (cell wall), the cell cannot dessicate, and nutrients are readily absorbed through a semi-permeable cell wall. Life on Earth began by at least 3.8 Ga ago (Mojzis et al., 1996), perhaps by 4.1 Ga (Bell et al., 2015), and single-celled life slowly evolved over at least 3 billion years before increasingly complex multicellular life evolved in Neoproterozoic time. Colonies of unspecialized cells have existed since 3.2 Ga as stromatolites (Lowe, 1994) but colonies of specialized cells – metazoa – did not evolve until sponges appeared in Late Neoproterozoic time (Wang et al., 2010). From this time forward, evolution of larger and more complex metazoans accelerated. It is not clear what was responsible for the increased evolutionary pace. It may have reflected increased environmental pressure from especially the ~635 Ma Marioan glaciation (Xiao, 2004), or it may have resulted from the beginning of sexual reproduction (Butterfield, 2000), or the beginning of plate tectonics in Neoproterozoic time may have been important (Stern, 2005).

We cannot imagine what environmental pressures might occur on exoplanets, but it seems likely that evolution from simple to complex life would broadly parallel that on Earth. A particularly important evolutionary breakthrough was the gut, one of the first outcomes of multicellularity (Stainier, 2005). A through-going digestive system involved cellular specialization, leading to formation of an outer protective coat (the ectoderm) and an inner digestive layer (the endoderm). The mesoderm, or middle layer, further specialized into bones, the other organs, and the brain. The gut was a biological innovation that provided competitive advantage by allowing early metazoans to process larger amounts of organic-rich sediments. This led naturally to burrowing infauna but the gut quickly was adapted for predation. An ancilliary benefit was the development of a front and rear on the animal, with the front the natural location for specialized cells sensitive to light, sound, and chemistry. With time and evolution these became eyes, ears, and olfactory-taste buds. Senses evolved rapidly, producing progressively greater data streams, requiring more processing by nearby concentrations of nerve cells leading to brains. Skeletons, musculature, and fins evolved. A broadly similar progression can be expected for the evolution of complex life on exoplanets. Up to this stage, metazoans required the ocean, thriving particularly on shallow continental shelves bathed by sunlight, with abundant plant life. Deep oceans overly thin, dense oceanic crust, but seawater also spills over low-lying continent, forming continental shelves (Emery, 1969). The abundance of continental shelves varies with the number of continents, which is greatest early in the Supercontinent Cycle (Worsley et al., 1984). Continental shelf area increased significantly when Rodinia began to break up ~825 Ma (Xi et al., 2008), and continued to increase as supercontinent fragmentation continued through Neoproterozoic time. This proliferation of continental shelves through Ediacaran and early Paleozoic time may have significantly accelerated chordate evolution, culminating in the evolution of jawed fish in Silurian time (~425 Ma).

Nearly all of the important adaptations needed to evolve advanced animals happened over 3.5 Ga of life in Earth's oceans, but technological species had to evolve on dry land. On a planet with large amounts of surface water, significant expanses of dry land requires continental crust, so distinct tracts of younger, thinner, basaltic ocean crust and older, thicker, granitic continental crust are required to allow both environments. Earth is the only planet known to have these two types of crust, although elevated continental-like areas and depressed ocean-like regions are present on other planets such as Mars and Venus including suggestions of felsic crust on Venus (Harris and Bédard, 2014). Earth's oceanic crust is basaltic, formed by seafloor spreading at mid-ocean ridges because of plate tectonics. Compared to oceanic crust, continental crust is almost an order of magnitude thicker, richer in silica and potash, more granitic and older, with a mean Nd model age of ~2.3 Ga (Hawkesworth and Kemp, 2006). Oceanic crust is ephemeral compared to continental crust, which is constantly redistributed over the Supercontinent Cycle as oceans are born, widen, narrow, and disappear. Does this continuous redistribution of continents and their shelves engendered by plate tectonics affect evolution?

There are three reasons why animals had to crawl out of the ocean to evolve into technological species: First, technological species must be able to manipulate materials, requiring dexterous appendages or hands. Hands would never have evolved in the ocean, only in the forest, where environmental pressure for grasping skill and strength was intense. Second, the development of the eye has driven much cerebral complexity, and – because light carries so much farther in air than in water – the brain-eye system evolved much more rapidly on dry land. Finally, the heavens are visible from land, mostly hidden from sea creatures. All creatures understand the sun daily cycle – the predictable appearance and disappearance of the sun - at some level, but the more complex monthly lunar cycle, the still more complex planetary cycles, and the subtle yearly star cycle took increasingly complex cognition skills that must have been key for stimulating abstract conceptualizations such as science and religion. Understanding the predictable movements of the night sky was a key development in evolution of our technological species. Plausibly, a similar scenario can be imagined on other exoplanets.

In summary, the optimal planet for advanced life to evolve would be a water-rich planet with two kinds of crust to provide abundant environments both above and below sealevel, with shallow, sunlit continental shelves between the deep ocean and dry land. Such a planet would allow life –once begun– to evolve to very advanced complexity in the oceans, which then further evolved on land to technological civilization (Fig. 3). Other evolutionary pathways may be possible, but we cannot imagine them yet.

4. Extinction and evolution

Evolution reflects adaptations of populations to a wide range of environmental stresses. On Earth, such stresses reflect both plate tectonic processes as well as phenomena that are unrelated to plate tectonics, for example bolide impacts. Environmental pressures can be great enough to cause extinctions, which stimulate evolution because these open up so much competition space (Erwin, 2001). The largest mass extinctions produce major restructuring of the biosphere wherein some successful groups are eliminated, allowing previously minor groups to expand and diversify (Raup, 1994). Insofar as extinction is a selective pressure on life, extinctions can be viewed for our purposes as unusually strong environmental pressures that provide valuable insights into the causes of natural selection and evolution. How are the environmental pressures likely to differ for planets with life, between stagnant lid planets and those with plate tectonics?

There are three essential causes of extinction – endogenic, exogenic, and biological. Biological pressures are exerted on a population of organisms by other organisms. This includes predation, competition for food, and parasites and infections. Biological pressures can partly reflect plate tectonic causes, for example by producing land bridges or oceanic gateways that allow predators, competitors, parasites, etc., access to a vulnerable species, but in many more cases biological pressures arise independent of plate tectonics. Endogenic causes come from solid Earth activity, and these depend on the tectono-magmatic style of the planet. This includes plate tectonic processes such as continental redistribution as well as flood basalt eruptions, which may be due to ascent of deep mantle plumes unrelated to plate tectonics (Jellinek and Manga, 2004; Whiteside et al., 2010). Exogenic causes originate in space. Cosmic radiation would be a powerful cause of extinction if not for Earth's powerful magnetosphere. Ultraviolet radiation is another strong exogenic evolutionary pressure, depending on the strength of the ozone shield (Cockell and Raven, 2007). Bolide impacts are also powerful exogenic life extinguishers and evolutionary pressure, for example the impact that caused the end-Cretaceous extinctions (Alvarez et al., 1980). Life may not have been possible until the Late Heavy Bombardment ended ~3.9 Ga

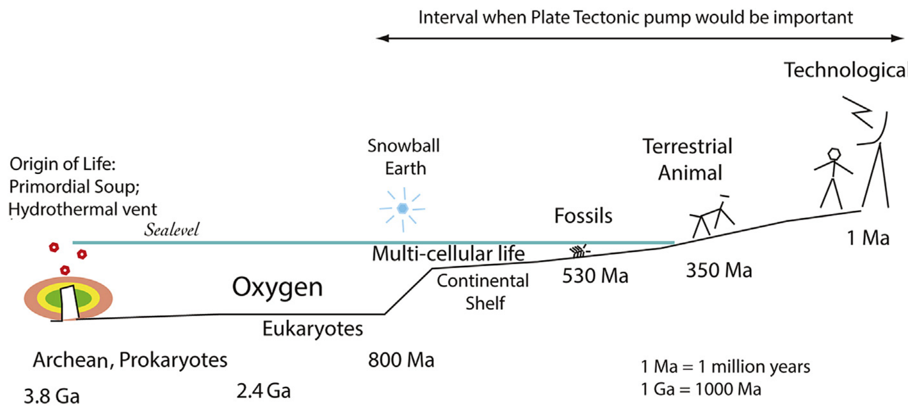

Figure 3. Cartoon summarizing evolution and when plate tectonics might have greatest effect on evolution, leading to the development of tool-using and then technological creatures.

(Abramov and Mojzsis, 2009), and bolide impacts probably bedeviled life throughout Archean time.

Plate tectonics isolates and reconnects landmasses, separates and reconnects oceans, builds mountain ranges and makes new shallow marine environments on continental shelves. These two types of physical reconfigurations of Earth's surface exert a powerful one-two evolutionary punch. First, physical isolation drives natural selection via allotropic speciation. Cracraft (1985) explored how speciation is controlled by lithospheric movements, as deduced from biogeographical premises: (1) speciation requires isolation; (2) isolation require geographic barriers, and these can be marine or terrestrial, depending on the organism; (3) plate tectonics builds, maintains, and reconfigures barriers; and (4) the formation rate of geobarriers on Earth reflects plate tectonics. Second, reconnections via continental collisions and opening of oceanic gateways leads to competition between species occupying similar niches, requiring adjustments of entire ecosystems. A planet lacking plate tectonics would be unable to provide nearly as many barriers and reconnections.

One final point should be made about environmental stresses originating from plate tectonic processes compared to those experienced on a stagnant lid planet. It is easy to imagine a non-plate tectonic environmental stress that obliterates life on a planet, for example a large bolide impact, nearby supernova, or an extremely large igneous event. In contrast, it is very difficult to imagine any environmental stress caused by plate tectonics that would be capable of extinguishing all life on the planet. Plate tectonic processes such as the redistribution of continents, growth of mountain ranges, formation of land bridges, and opening and closing of oceans provide a continuous but moderate environmental pressure that stimulates populations to compete, adapt and evolve. This is another "Goldilocks" situation for evolution of life on a planet with plate tectonics.

5. Evolution on planets with and without plate tectonics

We have not yet considered how plate tectonics can affect the pace of metazoan evolution, in particular the evolution of technological species. To do this, we must proceed from what we know about plate tectonics and evolution on Earth and combine this what we can imagine about how evolution might occur on an otherwise-similar stagnant lid planet with life but where continents and oceans are not continuously rearranged. Other environmental stresses are associated with plate tectonics, and we refer to all these as the plate tectonic "Pump".

We can build on general principles from the previous sections to better understand the plate tectonics impact on evolution via a thought experiment. Imagine two otherwise identical planets, both with similar life and ecosystems and with similar proportions of continents and oceans (Fig. 4). The planet on the right has plate tectonics (Fig. 4D–F) whereas the one on the left is characterized by stagnant lid tectonics with a single, all-encompassing lithosphere (Fig. 4A–C). Both would have magmatic and tectonic activity, although the styles differ; for example water-rich "arc" magmas would not exist on the stagnant lid planet and topographic relief would center around mantle plumes. Both planets are similarly suitable for life, with similar atmospheres and proportions of water and land and similarly situated in the "habitable zone" of a similar star; both are similarly protected from cosmic and ultraviolet radiation by magnetic fields and ozone layers. We establish similar simplified communities composed of three interdependent advanced life forms (plant "P", herbivore "H", and carnivore "C"; such a simplified ecosystem could exist on dry land or continental shelf) and let this community and these organisms evolve for a reasonable amount of time – a few hundred million years. Both planets are similarly subjected to other evolutionary stresses, such as bolide impacts, Milankovich cyclicity, hot spot/LIP eruptions, and biological interactions. The only difference between the two is that one planet has plate tectonics and the other is characterized by stagnant lid tectonics. Only the plate tectonic planet experiences continental rifting, opening of new oceans and closures of old ones, and recombination of continental fragments comprising a supercontinent cycle. Only the organisms and communities on the plate tectonic planet experience the evolutionary pressures of isolation and recombination.

If we let this experiment run for the ~300–500 Ma of a supercontinent cycle, would we expect to see significant differences in the course of evolution on the two planets? Yes, because of the additional evolutionary pressures that the ecosystems on the plate tectonic planet experience, specifically isolation leading to speciation and recombination leading to competition between organisms adapted to similar niches. Continental breakups isolate populations, which can be expected to evolve differently. Both land and marine communities are affected to different extents, depending on how mobile and specialized they are. Hardy, unspecialized single-celled organisms and larvae (which can be blown by wind and carried by currents) and migratory swimmers and flyers may be less affected by these reconfigurations, large land animals and specialized organisms adapted for certain climates are likely to be more affected. Continental collisions bring these communities back into contact and competition.

In contrast, the planet without plate tectonics will experience little change in the configuration of continents and oceans so that it is difficult to isolate populations and allopatric speciation is not

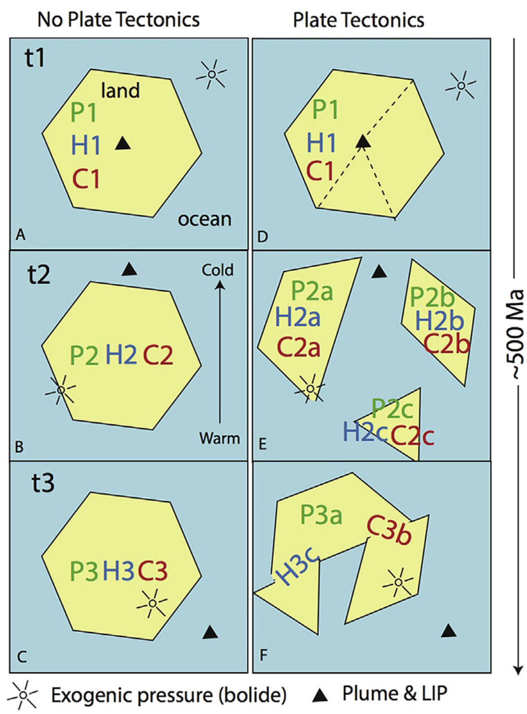

Figure 4. Cartoon of how natural selection and evolution vary on a simplified Earth-like planet with subequal areas of continents and oceans and three interdependent life forms (plant "P", herbivore "H", and carnivore "C") over a supercontinent cycle at three different times (1, 2, and 3) at ~100 million year intervals. Top of each panel corresponds to high latitudes (cool, arctic), bottom is equatorial (warm). Exogenic11 evolutionary pressures exist regardless of whether or not plate tectonics occurs, as does mantle plume activity including Large Igneous Provinces (LIPS). Left panels (A–C) show planet without plate tectonics, little change in continental configuration, only climatic isolation, few barriers, and slow climate change. Evolutionary pressures are dominantly biologic and exogenic. Right panels (D–F) show the situation for the same planet with plate tectonics over the course of a supercontinent cycle. This provides many opportunities for isolation, diversification under different conditions of natural selection, and evolution; this is "rift pump". Evolutionary rift pumping continues until continents collide, when different species comingle and compete and new ecological systems are established; this is "collision pump". Endogenic evolutionary pressures are more important and are dominated by plate tectonics effects.

favored. Whatever evolutionary pressures exist are dominated by N–S climate variations and stable geographic barriers. There is no seafloor spreading so sealevel changes little and slowly. Evolutionary pressures are dominantly biologic and exogenic, although endogenic stresses due to Milankovitch cyclicity and mantle plume activity would be expected.

Life on the planet with plate tectonics experiences the same biological and exogenic pressures but these are intensified by the Plate Tectonic pump. What is unique to Earth are the rapid changes in dry land geometry and distribution driven by plate tectonics, which serves to provide steady environmental pressure. Continental fragmentation leads to isolation, resulting in diversification under different conditions of natural selection, and thus provides for greater biodiversity; we can call this the "PT rift pump". Rift pumping increases allopatric speciation and this diversification continues until the continents recombine, when the many different species comingle and compete to establish new ecological systems. Continental recombination leading to competition between previously isolated species is called the "PT collision pump". It should be noted that PT rift and collision pumps will have the greatest effects on species that are easily isolated, for example shallow water invertebrates and terrestrial animals. Microbes, birds, fish, and plants with seeds that float or are blown by the wind will be less affected by barriers such as mountains, deserts, or bodies of water. Correspondingly, evolutionary pressures due to plate tectonics will have especially profound effects on more advanced life forms. Plate tectonics is a lesser evolutionary pressure early in the history of life (when prokaryotes and eukaryotes evolved) and more important late in the history of life (when intelligent life is evolving; Fig. 3).

6. Conclusions

Conclusions in a speculative essay like this are necessarily tentative. Earth is the only planet with life, technological civilization, and plate tectonics. Our imaginations are limited by this reality. Still, five main conclusions resulting from this study are noteworthy:

(1) Beginning life requires a planet with an ocean. Once life begins, a lot of evolution – including development of multicellular creatures with specialized cells and organs – can happen there, but evolution of technological species requires significant expanses of dry land.
(2) A planet with an atmosphere thin enough that stars are visible in the night sky is needed for technological species to study the galaxy and thus be interested to communicate with life on other planets.
(3) A silicate planet is likely to experience several tectonic styles over its lifetime, as it cools and its lithosphere thickens. These styles include magma ocean, various kinds of stagnant lid, and perhaps plate tectonics. Like life, plate tectonics is favored by abundant water.
(4) The presence or absence of plate tectonics has a profound effect on especially the evolution of advanced organisms. A planet with life and plate tectonics favors development of a more diverse biosphere that is more likely to include a technological species than an otherwise similar planet lacking plate tectonics.
(5) The search for technological species on exoplanets impels us to find planets with oceans and continents. Technological species are most likely to be found on bicrustal watery planets with plate tectonics and a reasonably clear sky.

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