The role of plate tectonics for surface habitability of rocky planets

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One of the biggest puzzles when it comes to the origin and evolution of life, is the peculiar characteristics that our Earth has in contrast to the planets and moons of the solar system, and what (if) we can learn from that. Earth orbits the sun at the right distance to allow for liquid water at its surface since the Moon-forming impact, but it also posses elevated land coverage that life was thriving on. The oceanic crust is recycled into the mantle on geological time scales by plate tectonics. Volcanic activity leads to continuous feeding of greenhouse gases into the atmosphere, compensated by carbon sinks via weathering in the global carbon cycle. The surface of Earth is shielded from harmful radiation by a magnetic field. None of the other bodies in the solar system show all of these characteristics – and for none of them were we so far successful in finding traces of life. Are all these astro- and geophysical processes and properties necessary for a planet to be habitable for any kind of life? Are they related to each other? Do we need plate tectonics and active volcanism together with a magnetic field for life to develop into complex beings such as us?

The impact that plate tectonics had on the evolution of Earth and life at its surface seems to be immense – without the rise of the continents (and continental shelfs), it is questionable how effective the photosynthesis would have become, and the impact of life on the atmosphere may have been much less – depending on the biomass that can evolve without any larger land coverage or shallow water regions around continental areas. The great oxygenation event, which on Earth may be a result of multiple effects (invention of photosynthesis, inefficient geochemical buffering of oxygen at the surface due to changes in crustal composition [1], change in redox state of Earth's mantle reflecting a change in outgassing products [2], change of submarine volcanism to subaerial volcanism [3]), seems to be strongly coupled to the existence (and possibly initiation) of plate tectonics at that time. In addition, the cooling effect that subducting plates have on the mantle, leads to an increased heat flux at the core-mantle boundary, which has a positive impact on maintaining a magnetic dynamo. Regulation of the atmosphere depends on both continental weathering (via life-enhanced silicate-carbon cycle) and seafloor weathering – but the latter process may have been dominant during early Earth [4], and does not need active plate tectonics but instead only replenishing of fresh, basaltic crust at the surface, which could as well be delivered by volcanic activity from hotspots or super-plumes in the mantle. If plate tectonics would not have been active on Earth, it is difficult to imagine that life would have evolved in the same way as it did, and maybe macroscopic forms of life, as they appeared on Earth few hundreds of million years ago, would not have been possible without plate tectonics.

Even though plate tectonics had a strong effect on the evolution of life on Earth, it is possible that planets are equally habitable in the absence of plate tectonics. It is worth investigating, how the evolution of Mars' surface would have changed, if Mars would have accreted more material to become comparable to Earth in size. Would it be impossible to find habitable niches at its surface without plate tectonics? If Mars would be more massive, its atmosphere would be expected to be much denser possibly with a stronger greenhouse effect, since atmospheric loss would have been less efficient during its early evolution, and more volatiles could have accumulated due to an increased delivery of volatile-rich material during the later stage of accretion [5,6]. Volcanic activity might still persist after billions of years, and would be more active than on Mars due to the larger mass (and therefore higher amount of radioactive heat sources in the mantle) – comparable maybe more to Venus' activity. Surface water would then be possible, if the atmosphere would have the right composition of greenhouse gases over long timescales, compensated by seafloor weathering. However, in the scaled-up Mars scenzario, an Earth-like dynamo activity would not be expected. But life is inventive and may be able to overcome the missing shielding of the surface from harmful radiation – for example by living at or in the seafloor of the ocean. These arguments are speculative in nature, but if Mars would be similar to Earth in size, it could be habitable over geological timescales even without plate tectonics, even though it is questionable how evolved life would have become under such circumstances.

However, the mass can also play a negative role for the evolution of the atmosphere and hence surface temperatures and potential surface habitability. For more massive super-Earths, plate tectonics may be therefore more important. If no substantial amounts of the primary atmosphere (from gas accretion and magma ocean outgassing stages [7]) survive, super-Earths may not be able to produce a dense-enough atmosphere to have liquid water at the surface, as long as they do not evolve into a plate-tectonics state [6]. For these planets, plate tectonics would be a necessary ingredient to build a dense-enough atmosphere for water to be liquid at the surface, and hence for (Earth-like) life to form and evolve.

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