Does a planet need plate tectonics to develop life?

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Plate tectonics may be a phase in the evolution of planets that has implications for the habitability of exoplanets, according to new research published this month in the journal Physics of the Earth and Planetary

Interiors.

Two of the things that make Earth unique in our solar system are that it has plate tectonics – with the surface broken up into a number of tectonic plates that drift around, moving continents and causing earthquakes – and life.

And there is a school of thought that these two are not unrelated.

Complex life on Earth took a long time to evolve; about 3.5 billion years by current estimates. This was possible as the Earth's surface has been habitable and in the temperature range for liquid water.

This is a remarkable level of stability, especially as the sun has grown 30% brighter over that same interval, meaning that Earth's atmosphere has evolved, becoming less of a greenhouse than it was 3 billion years ago.

Plate movements

Plate tectonics provides a mechanism for this global thermostat. Most volcanism on the Earth occurs at plate boundaries in response to plate tectonics. And the most important volcanic products by mass – by a large amount – are two greenhouse gases: carbon dioxide and water.

As they move over the Earth's surface, some plates get recycled back into the mantle, at places like the Marianas Trench in the Pacific Ocean.

Enormous amounts of water and carbonate (the mineral form of CO_2) get recycled back into the interior as they do.

Plate tectonics also form mountains, and one of the major sinks of CO_2 over geological time periods is weathering of mountains, where CO_2

dissolved in rainwater reacts with silicate minerals, forming new minerals, and drawing down atmospheric CO_2 levels.

In concert, these mechanisms act as a thermostat. If the Earth gets too hot, high levels of rainfall and erosion start bringing CO_2 levels down. If the Earth gets too cold and freezes over, the erosion mechanism stops.

But volcanism, due to plate tectonics, continues pumping CO_2 into the atmosphere, and levels build up, eventually melting the icecaps. It was this mechanism that allowed Earth to recover from a global ice age in the Neoproterozoic, about 600 million years ago.

Habitable planets

This association between habitability, and plate tectonics, has become so entrenched that the search for habitable exosolar planets has focused on super earths. These are rocky planets larger than Earth where the odds for plate tectonics were thought to be higher.

But the case is not so clear cut. Over the past decade, simulations of these super earths suggested that they may not have plate tectonics, but rather be in a stagnant-lid state, where a hot interior powers high levels of volcanism, but without moving plates.

Our recent work has looked at the question from an evolutionary viewpoint. How do Earth-like planets evolve from their hot, violent beginnings to their eventual cool, quiescent twilights, radiating their last heat to space?

We found that the evolutionary track a planet takes depends not only on its size, but on how it starts. For example, two planets identical in every other way, but with different starting temperatures, may evolve down very different evolutionary paths.

We also found that plate tectonics may simply be a phase in the evolution of planets, and that planets may begin and end with stagnant lids.

The video (below) shows a simulation of a planet from an initial post-magma ocean state, through more than 700 million years of evolution. The hot interior precludes plate tectonics, and the system evolves in a hot stagnant-lid state.

The planetary community has long accepted that as the Earth lost its internal heat, it would eventually settle into a quiescent stagnant state much like Mars or the Moon today.

The idea that planets may begin in a stagnant lid, though, is more surprising.

Intuitively, this seems an inefficient way for a planet to lose heat. Recycling of plates today is extremely effective at cooling the mantle. Yet one of the main issues in the study of Earth's thermal evolution is that Earth must have lost its heat less efficiently in the past, to explain its current internal temperatures.

Look to Jupiter's moon Io

An early stagnant lid on Earth provides a mechanism for that. We even have an analogue for this behaviour in Jupiter's moon Io today.

Io is the most volcanic body in the solar system, a result of Jupiter's tidal influence, and it operates in a stagnant heat-pipe mode, where it loses its heat primarily through volcanic heat pipes rather than plates.

In a 2013 study, US scientists William Moore and Alexander Webb demonstrated that this regime may have operated under the conditions of the early stagnant Earth.

Resolving the issue for Earth is tricky, as the geological record for the first 500 million years – the Hadean Eon – is missing.

Later geology has been interpreted in the context of stagnant-lid episodes, interspersed by dramatic tectonic events, though this is still contentious. But while geology is lacking, we do have samples from the Hadean in the geochemical signature of the Earth and in tiny mineral grains of zircon.

Zircons have provided incredible insights into the makeup of Hadean rocks, and the existence of surface water 4.4 billion years ago, but they are equivocal when it comes to determining tectonic state.

The most recent work suggests they may be crystallising from melt sheets formed by meteorite impacts on the early Earth.

In contrast, the long-lived isotopic signatures of Hadean processes survived for billions of years in Earth's mantle, and are recorded in ancient volcanic rocks. The mixing of this material provides an important constraint for the tectonics of the Earth, and supports the idea that the Earth was largely stagnant.

If our conclusions are right, and plate tectonics is an adolescent phase in the evolution of Earth-like planets, then this has big implications for habitability.

Life on Earth

Life evolved on the Earth very early. There is evidence in carbon isotopes from Hadean zircons, and solid fossil evidence from 3.5 billion years ago. It probably evolved on a planet with a stagnant lid, not plate tectonics.

Volcanic degassing evidently provided enough of a greenhouse effect to keep the planet from freezing, despite lower atmospheric pressures. This was probably helped by low levels of mountain building and subduction of carbonate material, both of which need tectonics.

The evidence we have suggests most of the Earth's continents were below sea-level before 3 billion years ago, and so Earth's atmospheric CO_2 had nowhere to go.

These conclusions also impact the search for habitable exoplanets. For a long time there has been an ingrained assumption that habitable exoplanets must possess plate tectonics like the Earth.

The simplistic view of Venus supports this, as it does not have plate tectonics, and is extremely inhospitable to surface life. Yet Venus and Earth may have diverged for very different reasons early in their history.

It is entirely possible that the best analogue for early Earth, on which life evolved, is a warm, stagnant-lid planet in a distant star system. This increases the exploration space for habitable planets, and in doing so, the chances of life elsewhere in the universe.

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