

The plate tecton

A major factor in Earth's habitability are plate tectonics – the movement of the continents. With the discovery of many rocky planets larger than our own orbiting other stars, **Michael Chorost** asks, could super-earths also have plate tectonics?

▲ An artist's impression of a super-earth planet. Image: David A Aguilar (CfA).

The Earth moves. Volcanoes erupt where crustal plates are forced down into subterranean magma. Continents pull themselves agonisingly apart and molten rock bursts out of the widening seams between them. Earthquakes rattle the land. Tsunamis sweep the seas. Continents vanish. New continents are born. The Earth is riven by plate tectonics.

And it is alive, with a flourishing biosphere. Could there be a connection between Earth's lively crust and its equally lively biosphere? "I don't think it's an accident that Earth is such an active planet and it's also so flagrantly alive," says David Grinspoon, an astrobiologist at the Library of Congress in Washington, DC. "There are things that plate tectonics does for the Earth that

seem to facilitate it being such a great environment, at least for our kind of life."

Many scientists agree that plate tectonics are important to biology. "Plate tectonics creates a stable environment for a very long time," says Hein van Heck, a geophysicist at Cardiff University. On the one hand, he explains, it counteracts the runaway greenhouse effect. When an atmosphere gets warmer, more of its carbon dioxide is absorbed into the rocks being subducted into the mantle and thus is removed from the atmosphere. On the other hand, plate tectonics also counteracts runaway glaciation (the 'Snowball Earth' phenomenon) by pumping carbon dioxide back into the air via volcanoes. Plate tectonics is thought to act like a thermostat on long timescales, keeping

a planet's atmosphere in the right temperature range for liquid water.

It is thought to have other life-friendly effects as well. "It recycles nutrients from the interior to the surface and atmosphere and then back into the interior," says Grinspoon. "There are all these cycles, the carbon cycle, the nitrogen cycle and others that over the long-run are facilitated by this kind of restless churning of the Earth." Volcanoes spew water, nitrogen and oxygen into the atmosphere. Under the seas, the heat of plate boundaries fuels the black smokers that churn a rich blend of nutrients into the sea, feeding waterborne ecosystems.

Do planets need plate tectonics to be life-friendly? No one knows for sure, but it is known that Venus and Mars have no plate tectonics. They are, in the charming jargon of geophysicists, 'stagnant-lid' planets whose crusts have locked into place. It may not be a coincidence that Venus has a runaway greenhouse effect from hell, with carbon dioxide at 92 atmospheres and a surface temperature of 462 degrees Celsius. Meanwhile, Mars is a cold, dry desert. Is it because they lack a restless crust that both stirs things up and keeps things stable? It may be that without the constant churning of plate tectonics, a planet just goes bad.

Warfare

Geophysicists and astronomers are now asking, with increasing urgency, "Can 'super-earths' have plate tectonics?" At least ten rocky planets larger than Earth are known to be orbiting in habitable zones and the question is whether their larger size guarantees or prevents plate tectonics. Since nothing is known about their histories and compositions, scientists have revved up models of planetary interiors based on what's known about Earth. So far, the answers in the literature are entertainingly diverse: yes, no, and maybe.

In fact, the years 2007–2013 could be called the 'Plate Tectonic Wars',

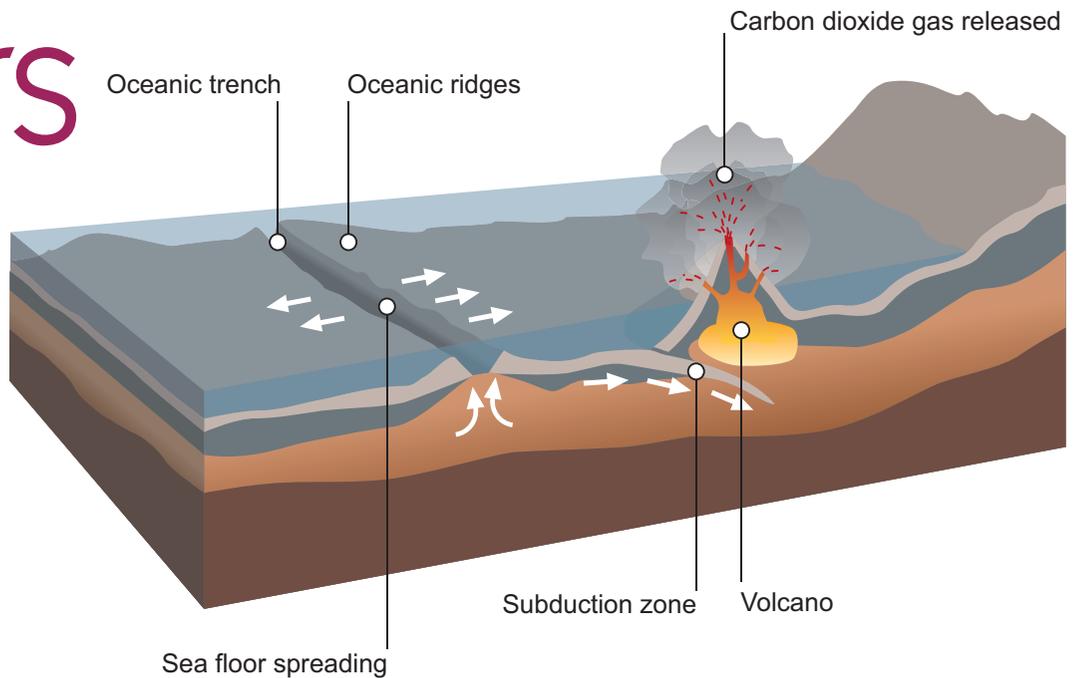
Plate tectonic wars

with lengthy papers coming out with answers that totally contradict each other. Of course super-earths will have plate tectonics, said Valencia et al in 2007. That's ridiculous, retorted O'Neill et al in the same year; the higher gravity will make the crust too strong to break and subduct. That's right, added Kite et al in 2009: it's also because they're too hot. Actually, replied Korenaga in 2010 and van Heck and Tackley in 2011, liquid water on the surface may be more important than size, because it lubricates plates and lets them move. You're all wet, said Stein et al in 2013. Heat's the problem. And on it goes.

Why the disagreement? Linda Elkins-Tanton, the Director of the Department of Terrestrial Magnetism in Washington, DC, says with a laugh, "The reason they fundamentally disagree is that we don't understand plate tectonics." To be sure, the Earth is right there, under our feet, and scientists have probed it for decades with seismic instruments and drills. Its gross make-up is fairly well known. But, she says, "There are relatively few well-understood boundary conditions."

Hein van Heck explains further in his Dutch-flavored English, "We cannot model exactly a planet." He points out that there's a lot of things geologists don't know about Earth, let alone super-earths they've never laid eyes on. For example, they don't fully understand the viscosity of the mantle underneath the crust, since it is hard to reach with a drill and its extreme temperatures and pressures can't be reproduced in laboratories. So, van Heck says, "We have to make simplifications. Most models start with Earth and make it bigger."

That's where the trouble starts. One can't simply scale Earth up. Quantity changes quality; doubling the radius of a planet increases its volume by a factor of eight, changing the relative impact of basic factors such as mass, gravity and heat. Plus there are still too many unknowns. Papers reach different conclusions because they are extrapolating from



different simplifications of Earth's plate tectonics, with different values for factors like viscosity, crustal depth and radioactive heat generation. Brad Foley, a doctoral student in geology and geophysics at Harvard, agrees. "There's so much uncertainty about what a super-earth will be like. If you just scale up Earth, you immediately run into issues. You don't know what its mantle temperature will be, or what its viscosity will be since the pressure is much higher." He also points out that super-earths could have more heat-emitting radioactive elements per unit volume, having held onto more of them while forming.

And then there's the variable of the type of star a planet orbits; the ratios of elements in a planet orbiting a small, cool red dwarf star may be different from those in one orbiting a much

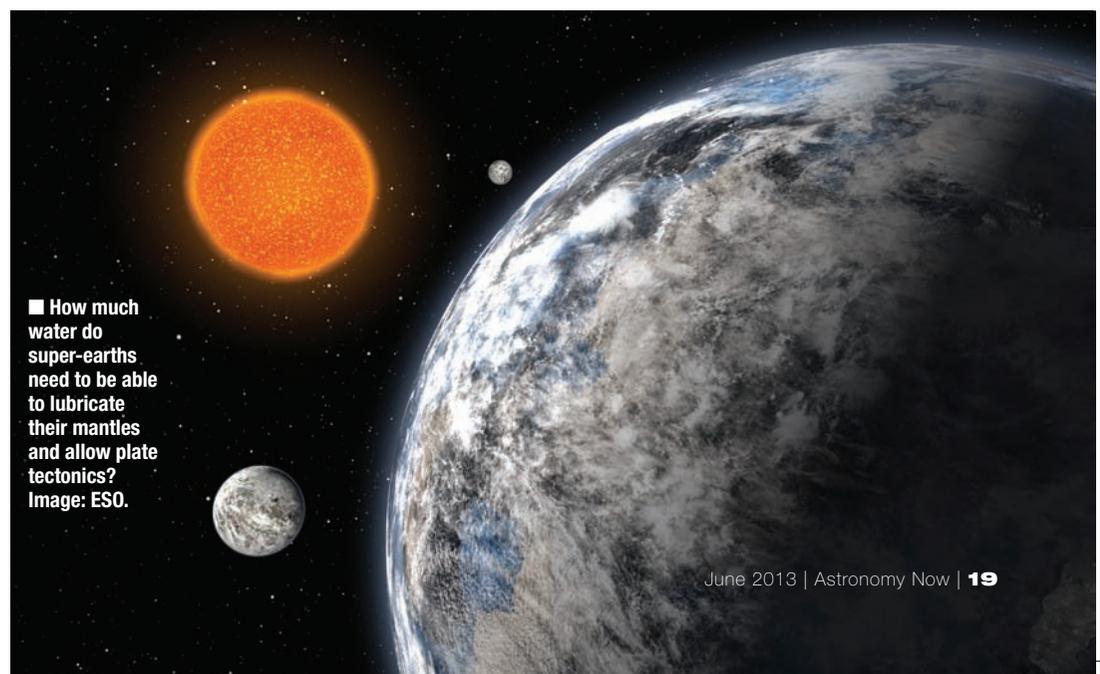
▲ **Plate tectonics are vital for moderating our climate over long timescales. Carbon, a greenhouse gas, is absorbed out of the atmosphere by rock, causing cooling. The carbon makes its way to the seafloor where it sinks via subduction zones where one continental plate slips under another. At a later time, this carbon dioxide is then regurgitated by the Earth in volcanic plumes, from where it re-enters the atmosphere, causing warming again. The question is, can super-earths also have plate tectonics? AN graphic by Greg Smye-Rumsby.**

brighter Sun-like star, and that could affect plate tectonics. Given all these uncertainties, at this point scientists aren't really predicting whether super-earths will have plate tectonics. They're actually just trying out different models and seeing what happens.

Water required?

Brad Foley is in the pro plate-tectonics camp. His model shows that super-earths will have plate tectonics. That's basically because they will be denser and heavier, due to their higher gravity. That makes it easier to 'damage' the crust and force pieces of it down into the depths.

However, Foley noted in response to a question during a talk at the Department of Terrestrial Magnetism that his model downplays the role of surface water – and that's controversial.



The plate tectonic **wars**

Some geologists believe that Earth's oceans are crucial to its plate tectonics. Water lowers the melting point of rock, weakening the strength of the crust and making it easier for plates to move relative to each other. If that is true, then a dry super-earth might be out of luck. (That would be a problem for Vulcan, which in *Star Trek's* mythology is larger and drier than Earth. It may be a good thing for science that J.J. Abrams did away with it in his first *Star Trek* movie.) "Most previous work says that water plays a direct role in plate tectonics," Foley says. "But I think the surface temperature may be more important than water." Water does play an indirect role, he concedes, as precipitation that causes rocks to weather and absorb carbon dioxide.

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While the Plate Tectonic Wars have been useful for exploring models, they haven't answered the question of whether plate tectonics are actually necessary for life. During the Q&A after Foley's lecture, David Grinspoon asked pointedly: do our arguments about plate tectonics betray a failure of imagination about what life needs? Perhaps, he suggested, aliens living happily on stagnant-lid planets would think that Earth is too scary and unstable for complex life, with its constant volcanoes, earthquakes and tsunamis. In an interview afterward Grinspoon said, "I could do a thought experiment of intelligent species who evolved on some other planet and developed science saying, 'Well, there's no way you could have life on one of these planets with plate tectonics, because that's just so unstable, that's crazy!' The crust is moving around and the climate oscillates and it's really fickle and unstable and unsuitable for life. I think that we're used to Earth and its kind of activity and, therefore, we assume that a planet's life has to be like this. But I'm not sure we know enough to say that's true."



▲ **Sunset on a super-earth orbiting a red dwarf in a triple star system. Are those alien mountains formed by plate tectonics or some other means? Image: ESO/L Calçada.**

Not the only way

Ultimately, the stakes are about life as well as geology. In their 2000 book *Rare Earth*, Peter Ward and Donald Brownlee argued that Earth's ability to evolve complex life comes from an unlikely combination of properties. For example, Earth is inside its star's habitable zone and it has a large moon that stabilises its axial tilt and it has plate tectonics that stabilise its atmosphere. Such a combination is bound to be rare, they argued, and therefore complex life should be rare too.

Grinspoon disagrees. Eventually, he thinks, we may find that planets have other ways of evolving complex life. "Any planet with complex life will have quirky and somewhat unique characteristics in its own natural history," he says. "Whatever life evolves there will be shaped to cleverly exploit those idiosyncrasies. And then when life gets complex enough to come to consciousness and looks back on that natural history, it will say, 'Oh good heavens! Look at all of these things that are unusual about the history of our planet. Only on a planet like this could complex life develop'."

So the debate over plate tectonics on super-earths is really a two-levelled debate: first over whether it is possible, and second over its importance for complex life. No one is claiming that either level can be settled by maths alone; clearly, much more information is needed. Yet even in its nascent form, it signifies that the search for life away from Earth has attained a new level of complexity and tangibility. These are real worlds. They can be explored with instruments that exist now and with ones soon to come.

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▼ **The legacy of plate tectonics on Earth. This image is of a region in north-east Iceland, where the Mid-Atlantic Ridge cuts through. The tabletop mountains are formed by volcanic activity. Could such landscapes exist on super-earths?**

