THE TIMING OF HABITABILITY FOR EARTH- AND VENUS-LIKE PLANETS: THE ROLE OF TECTONIC COOLING EFFICIENCY J Seales[1] and A Lenardic [1], [1]Department of Earth, Environmental and Planetary Science, Houston, TX, jds16@rice.edu.

The ability of a planet to maintain surface water, key to life as we know it, depends on solar and planetary energy. As a star ages, it brightens and delivers more energy to a planet [1]. As a planet ages, the exponential decay of radiogenics produces less internal heat, which leads to cooling. For the Earth, interior cooling connects to plate tectonics - the surface manifestation of convection within the Earth's interior [2]. This process cycles volatiles (CO2 and water) between surface and interior reservoirs, which affects planetary climate [3]. Cycling rates depend on the efficiency of plate tectonic cooling. That efficiency remains debated, as multiple hypotheses have been put forth [4].

Here we evaluate the range of temporal entry points into the classical habitable zone based on validated hypotheses. Geological proxy data [5,6,7,8] constraining Earth's thermal history allow us to validate certain hypotheses in light of model and data uncertainty. Those models define a distribution, that accounts for variations in tectonic efficiency, for terrestrial exoplanets akin to Earth. Feeding this distribution into climate models [3,9,10] indicates that the time at which habitable conditions are established can vary by billions of years. Planets of the same absolute age can reside and not reside within the classic habitable zone due to differences in tectonic cooling efficiencies.

The full model population allowed us to calculate the uncertainty in surface temperature. From that, we could calculate a probability distribution for the time at which habitable conditions are established (Figure 1). The probability peak indicates that exoplanets could become habitable billions of years after formation. An implication for planets that form around stars whose early evolution is unfavorable for planetary life is that variations in tectonic efficiency can allow these planets to become habitable later in their energetic histories. The distribution in Figure 1 holds for planets in Earth's orbit. We can also consider how changing this orbital distance impacts our outcomes. We find that if Earth were in Mars' orbit, it would have remained too cold for the existence of surface water. However, if Earth were at Venus' orbital distance, all validated models would have been in the habitable zone from the start.

Though Venus is often considered Earth's twin, it is not habitable at present. The thermal history of its mantle differs from that of Earth. Rather than having continuous overturns associated with plate tectonics, Venus likely had episodic overturns throughout its history [11]. This is hypothesized to have potentially transitioned Venus from habitable to the current climatic state [12]. We can account for such thermal histories using parameterized convection models [13] and find that an episodic Venus could have been habitable early in its history for a range of assumptions. This result along with the findings of others suggesting stagnant lid planets can be habitable [14,15], and our own existence on Earth suggest that something more fundamental than tectonic

regime be considered in evaluating the habitability of exoplanets. We propose that volatile cycling is the more fundamental issue, and that different tectonics modes have the ability to lead to volatile cycling histories that have enough overlap such that temperate conditions can be maintained
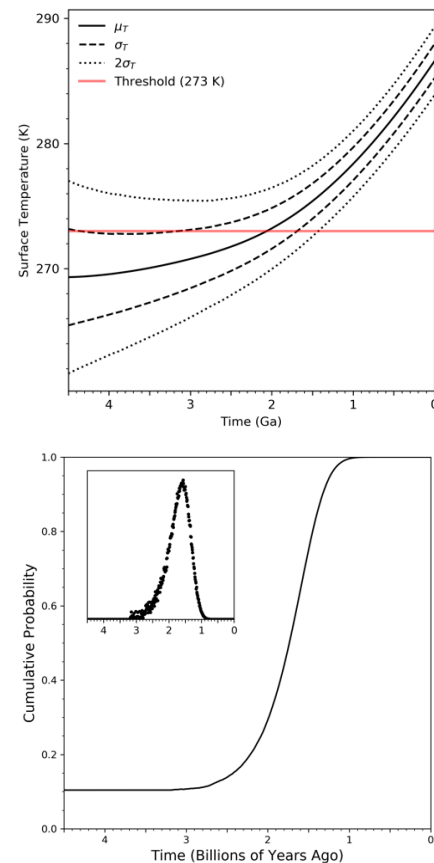

Figure 1: Surface temperature uncertainty over the lifetime of Earth (top) and the cumulative probability of Earth's entry into the classic habitable zone (bottom).

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