Life Potential on Early Venus Connected to Climate and Geologic History. M. B. Weller[1], A. Lenardic[2], and M. Jellinek[3], [1]Institute for Geophysics, Jackson School of Geosciences The University of Texas at Austin, Austin, TX (mbweller@ig.utexas.edu), [2]Department of Earth Science, Rice University, Houston, TX 77005, USA, [3] Department of Earth, Ocean, and Atmosphere, University of British Columbia, Vancouver, BC, Ca.

Introduction: A key observation and open question in the Earth and Planetary Sciences is that the Earth is seemingly unique in that it exhibits plate tectonics and a buffered climate allowing liquid water to exist at the surface over its geologic lifetime. While we know plate tectonics is currently in operation on the Earth, the timing of its onset, the length of its activity, and its prevalence outside the Earth are far from certain. Recent work suggests that the Earth has not always been within a plate-tectonic regime, and that it has evolved over time. Multiple lines of geochemical and geologic evidence, as well as geophysical models of planetary evolution, suggest the Earth initiated in a stagnant-lid (one plate-planet), followed by an "adolescent" episodic-lid (alternating between stagnant and mobile-lids), before settling into a "mature" modern style of plate-tectonics (mobile-lid) [*e.g.*, 1 – 6]. This implies that life and habitable conditions have existed on the Earth during episodic behavior. Modeling of an episodic early Earth has further shown habitable climates to be viable [7].

Currently, Venus shows no clear evidence of Earth-like plate tectonic activity or surface conditions. Observations reveal a world that has both a thick 92 bar atmosphere, comprised of 96.5% CO2 and surface temperatures of ~740 K, and been resurfaced by vast volcanic plains that cover ~ 80% of the surface, which are thought to have been emplaced in the last 300 – 1000 Myr [8 – 10], perhaps 'catastrophically' [9, 10]. These observations, along with inferences of limited large scale shortening [11], are consistent with suggestions of an episodic-lid regime [12 – 14].

If an early episodic Earth could support a habitable climate [7], what of Earth's "twin", Venus? Could an episodic Venus have been habitable? Here we examine this possibility, and show links between atmospheric evolution, habitability, and the deep interior.

Evolution of the Surface/Atmosphere System:

Figure 1 shows a general (simple) transition from a long-lived (early; steady-state) stagnant-lid, characterized by low mobility, low melt, and high internal temperatures, to a mobile-lid regime, characterized by high mobility, moderate to high melt, and lower internal temperatures (see Figure 1 for a description of model parameters and metrics). Early planets are highly likely to operate within a stagnant-lid regime [*e.g.*, 3 – 6]. Therefore, internal heating rates, a proxy for ageing, are decreased from high to intermediate values, holding all other values equal, to allow for mobile behavior to develop through a transitory (episodic) overturn (red-box: Figure 1). This example model is taken as the starting condition for the climate models. The overturn, and associated melting (panel 2 green curve, Figure 1), results in a global pCO_2 increase of 50 – 100x (calculated following the description in Figure 1).

The effects of an increase in pCO2 from a melt source on a proxy climate system are shown in Figure 2. In this case the proxy is Earth-like in land/water distribution and initial surface temperatures, assuming early Earth and Venus are otherwise identical (*e.g.*, not a runaway greenhouse), consistent with inferences from models of planetary evolution [*e.g.*, 3], and the suggestion of liquid water in Venus' past [*e.g.*, 15]. Age acts as a proxy for distance. Therefore, Venus' response at 0.72 AU acts as a later stage (older) Earth. Increasing pCO2 for an early Earth distance planet (1 AU) results in an early potential for a snowball state, but an increasing potential for climates that allow for liquid water as the solar luminosity increases (bottom to top branch as the Sun ages, Figure 2). In comparison, Venus type solutions, have a decreased likelihood for temperatures that allow for global glaciations, and instead favor temperatures in the past that allow for liquid water (*e.g.,* top branches of Figure 2), suggesting early Venus may have had an advantage over the early Earth for predicted surface temperatures, and the potential for liquid water. As the Suns luminosity increases, the potential surface temperature is pushed to the higher extremes of the warmer surface temperature branches (upper left corner Figure 2).

This work suggests that an episodic Venus has the potential to allow for liquid water, and consequently habitability. If Venus could support life, it suggests a fundamental rethinking of plate-tectonics links to habitability, and how habitable zones are defined, that is Venus is at the edge of the current habitable zone because it currently does not have liquid water, not because it is inherently incapable of having liquid water at present [*e.g.*, 6].

The potential of a life-bearing Venus illustrates the pressing need to constrain the tectonic and atmospheric evolution of Venus, in order to validate, or refute these ideas. If episodic, as has been recently suggested, blocks of intact surface can survive episodic resurfacing over geologic time scales [22], indicating that a record of older terrains, formed potentially under different atmospheric and tectonic conditions, are waiting to be discovered at the surface.

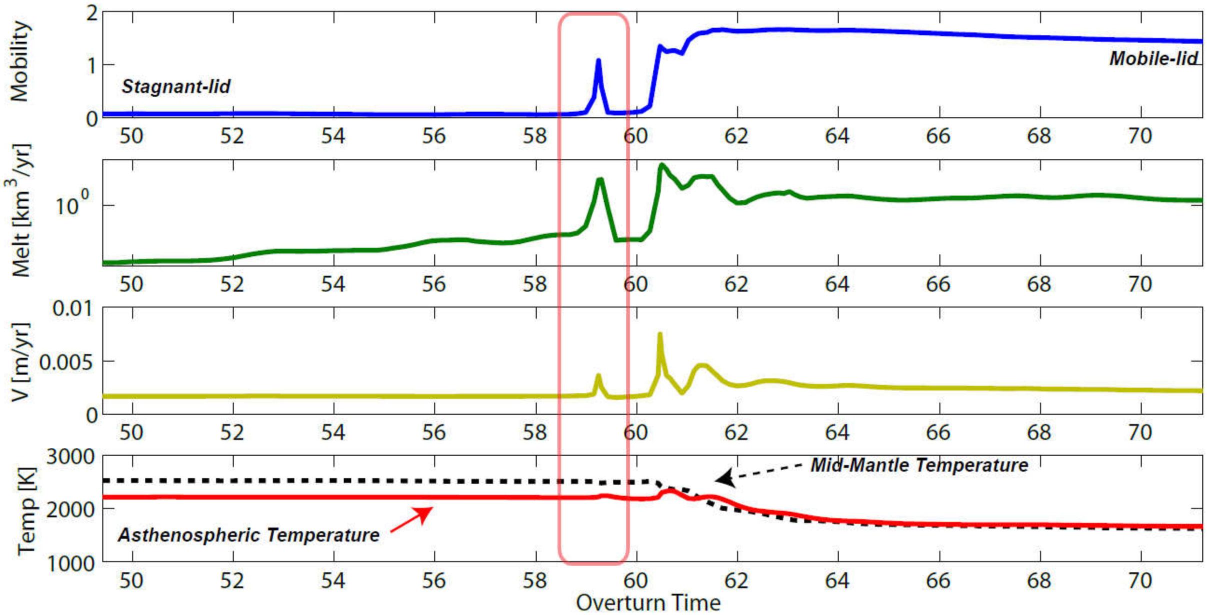

Figure 1: Selected results from the finite element code CitcomS [16 – 18] showing a global tectonic regime evolution (for fixed parameters). Red bar indicates a transient yielding event (episodic overturn). Quantities with [ ] denote dimensional values, all other values are non-dimensional. Top panel, surface versus system velocities. Where Mobility ≥ 1 indicates a mobile-lid and a Mobility ≤ 0.1 indicates stagnant-lid. Second panel, melt production, calculated in post-processing using solidus and liquidus relationships [19]. Third panel, bulk system velocity. Fourth panel, temperatures in the upper mantle (red line) and mid-mantle (dashed black line). The overturn time (x-axis, all panels) corresponds to the time a parcel takes (on average) to traverse the mantle. The Rayleigh number (definition for basally heated systems using the viscosity at the system base) is 10^5, with a temperature-dependant viscosity contrast of 10^4, an input internal heating rate of 28 (decreased from higher values), a yield strength of $4.25 \cdot 10^4$, and the non-adiabatic temperature contrast is 3000 K.

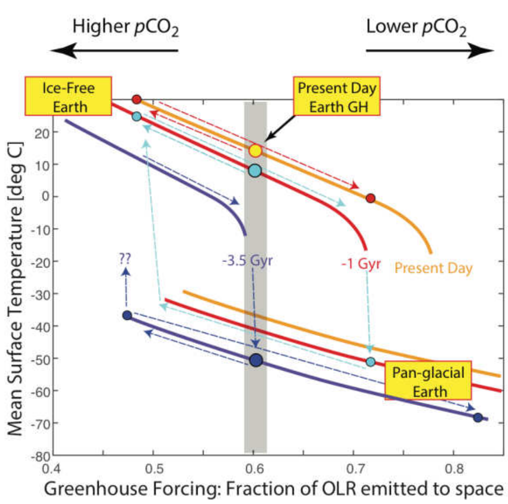

Figure 2: (Reproduced from [7]) Earth's potential surface temperature response to an O(100) increase in pCO2 from melting sources [7, 20], assuming that the unperturbed greenhouse forcing is fixed at a present-day Earth values (large-filled circles). The signal for current day insolation, does not alter the climate of the planet to a pan-glacial or an ice-free state (small red-filled circles and dashed arrows). 1 billion years ago, the signal does drive the model climate to vary between variably warm solutions and a pan-glacial state

Figure 2 (continued): (light blue-filled circles and dashed arrows). Further back in time, 3.5 billion years ago, the pCO2 signal carries the globally glaciated model planet into a snowball state and also potentially out of this solution (dashed arrow with a question mark). Note: Age is a proxy for distance. Venus-type solutions will be shifted to younger ages do to its closer stellar proximity.

References: [1] Debaille et al (2013), EPSL, 373, 83–92; [2] O'Neill & Debaille (2014), EPSL, 406, 49-58; [3] Weller et al., (2015), Earth Planet. Sci. Lett. 420, 85–94; [4] O'Neill, et al. (2016), Physics of the Earth and Planetary Interiors, 255, 80-92; [5] Lenardic et al., (2016), Astrobiology 16(7), 9 pp.; [6] Weller, M.B., and Lenardic, A., (2017). Geoscience Frontiers 9, 91e102 ; [7] Lenardic, et al., JGR 25th anniversary issue, E005089. [8] McKinnon et al. (1997) , Venus II, Arizona Univ. Press, pp. 969–1014; [9] Schaber, et al. (1992), JGR, 97, 13257–13301; [10] Strom et al. (1994) , 99, JGR 10899–10926; [11] Kiefer, LPSC 44, # 2541; [12] Schubert et al. (1997), Venus II, Arizona Univ. Press, pp. 1245–12888; [13] Nimmo and McKenzie (1998), Annu. Rev. Earth Planet. Sci. 26, 23–51; [14] Moresi and Solomatov, (1998), JGR, 133, 669-682; [15] Way et al., (2016), GRL, 10.1002/2016GL069790; [16] Moresi and Solomatov (1995), Physics of Fluids,7 (9), 2154-2162. [17] Zhong, et al. (2000), JGR, 105, 11063–11082, [18] Tan, E., et al. (2006), G3, 7, Q06001. [19] Hirschmann, M., Geo-chem. Geophys. Geosyst., (2000), 2000GC000070; [20] Jellinek and Jackson (2015), Nature Geoscience. [18] Weller, M. B. & Kiefer, W. S., LPSC, 47, # 1663.