DOES TERRESTRIAL LIFE 'FOLLOW THE WATER'? E. G. Jones[1] C. H. Lineweaver[2], [1]Research School of Astronomy & Astrophysics, Australian National University, Mount Stromlo Observatory, Cotter Road, Canberra, ACT, 2611, Australia. eriita@mso.anu.edu.au. [2]Planetary Science Institute, Research School of Earth Sciences, Research School of Astronomy & Astrophysics, Australian National University. charley@mso.anu.edu.au.

Introduction: NASA's "follow the water" strategy for Mars exploration is based on the observation that all terrestrial life requires liquid water during some phase of its life cycle [1]. This strategy however can be refined by including other fundamental requirements of life, such as energy [2]. We have quantified the habitability of liquid water on Earth in a pressure and temperature diagram and located where uninhabited liquid water environments are [3]. Several factors that limit the habitability of liquid water and have been previously studied include temperature [4], water activity [5], nutrients [6], pore space [7] and free energy availability [8,9], however no empirical study has previously quantified what fraction of liquid water environments on Earth are uninhabited by life. To this end we have developed a pressure-temperature representation model of the Earth.

Results: Our model consists of a pressure-temperature (P-T) phase diagram of all terrestrial environments superimposed on the phase diagram of water (Fig. 1). It shows the regions of phase space where there is both Earth and liquid water. It also shows the regions where there is Earth but no liquid water, and where there could be liquid water but there is no Earth. There are two liquid water phase models in Fig. 1, corresponding to 'ocean salinity' (dotted line) liquid water and an estimate of the 'maximum liquid range' (thick solid line) in P-T space. 'Maximum liquid range' is appropriate for concentrated briny inclusions and thin liquid films in ice and permafrost on the Earth's sur-

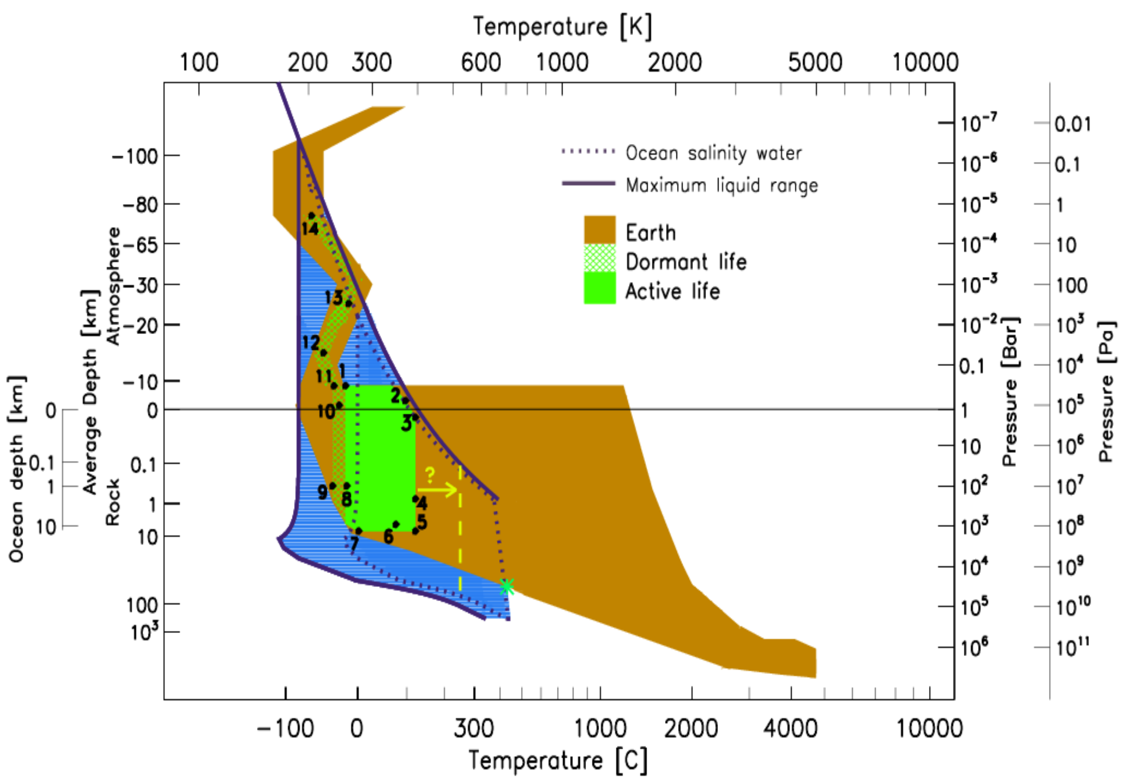

Figure 1. Superposition of inhabited terrestrial environments (in green) and all terrestrial environments (in brown) on the P-T diagram of water. Life does not seem to inhabit the full range of terrestrial environments where liquid water is available. The upper temperature limit for life, currently 122° C, excludes life from the hottest and deepest water. The question mark and the yellow arrow pointing from the current upper temperature limit of life (T_{life} < 122 ˚C) to the vertical dashed yellow line at T= 250˚C represents the change that would occur in this diagram if life is found at T = 250˚C. See [3] for more detail.

face. The phase space of life on Earth (green) is also shown. We have made a provisional distinction between active (solid green) and dormant (hashed green) life. Although spores and other dormant life forms have evolved to withstand extreme environmental conditions, they cannot complete their life cycles in those conditions. In constructing the inhabited regions of phase space, we have assumed that the T < 122 ^{o}C upper limit to life [4], and that the T > -20 ^{o}C lower limit to active life [10], are both valid over a broader range of pressures than has been fully explored by microbiologists.

The green asterisk in Fig. 1 represents our estimate of the hottest and deepest water on Earth at T~ 431˚ C and P ~ 3 x 10^4 bar, corresponding to a depth of ~ 75 km. This limit was obtained from the intersection of the phase space occupied by the Earth with the phase space of liquid water. Liquid water is stable at higher pressures and temperatures than this limit, but terrestrial environments at these pressures and temperatures do not exist. As this is the limit for liquid water on Earth, it represents the deepest possible extent of the terrestrial biosphere.

Fig. 1 can be used to quantify the potential limits of the terrestrial biosphere, such as what fraction of the volume of the Earth is inhabited. The biosphere extends for ~ 10 km above the average surface and extends for ~10 km down in the oceans and ~ 5 km down into continental crust. Assuming oceans occupy 70% of the surface and continents 30%, the biosphere occupies ~ 1% of the volume of the Earth. Thus, after 4 billion years of evolution, the terrestrial biosphere seems to have been unable to extend into ~99% of the volume of the Earth. What fraction of the volume of the Earth where liquid water exists, is known to host life? The shell of the Earth which contains liquid water is ~75 km thick (green asterisk in Fig.1). Using ~5 km and ~10 km for the thickness of the crustal and oceanic biospheres respectively and ignoring the atmosphere, we obtain the result that ~12% of the volume of the Earth where liquid water exists is known to host life. Thus, according to our current state of exploration, 88% of the volume of the Earth where liquid water exists is not known to harbor life. If the high temperature limit for life is increased to 250 ^{o}C, the thickness of the biosphere would approximately triple to include ~38% of the volume of the Earth that has liquid water.

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