To What Extent Does Terrestrial Life ‘Follow The Water’?

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ABSTRACT

Terrestrial life is known to require liquid water but not all terrestrial water is inhabited. Thus, liquid water is a necessary, but not a sufficient condition for life. To quantify the terrestrial limits on the habitability of water and help identify the factors that make some terrestrial water uninhabited, we present empirical pressure-temperature (P-T) phase diagrams of water, Earth and terrestrial life. We find that ~88 % of the volume of the Earth where liquid water exists is not known to host life. This potentially uninhabited terrestrial liquid water includes i) hot and deep regions of the Earth where some combination of high temperature ($T > 122^\circ$C), and restrictions on pore space, nutrients and energy are the limiting factors, and ii) cold and near surface regions of the Earth such as brine inclusions and thin films in ice and permafrost (depths less than ~1 km) where low temperatures ($T < -40^\circ$C) and/or low water activity ($a_w < 0.6$) are the limiting factors. If the known limits of terrestrial life do not change significantly, these limits represent important constraints on our biosphere, and potentially on others, since ~4 billion years of evolution have not allowed life to adapt to a large fraction of the volume of the Earth where liquid water exists.

Keywords: Biosphere -- Limits of life – Extremophiles – Water

INTRODUCTION

NASA’s “follow the water” strategy for Mars exploration (e.g. Hubbard et al 2002) is based on the observation that all terrestrial life requires liquid water during some phase of its life cycle (Rothschild & Mancinelli 2001). This strategy can be refined by including other fundamental requirements of life. Energy for example; Hoehler (2004), Hoehler et al (2007) and Shock & Holland (2007) describe how “follow the water” can be complimented by a “follow the energy” approach. Here we refine the “follow the water” approach by empirically quantifying the boundaries between the habitable and uninhabitable water on Earth. Research on extremophiles has revealed apparent limits of temperature, water activity, nutrient, pore space and free energy availability (Baross et al. 2007, Jakosky, 2007). These factors are implicated in making some water uninhabitable. However no empirical study has comprehensively quantified the fraction of uninhabited terrestrial water nor comprehensively described where these wet uninhabitable environments are. To this end, we have developed a model for

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presenting the Earth and Mars on a pressure-temperature (P-T) diagram (see Jones & Lineweaver, 2008).

**FIG. 1. Water, Earth and Life.** In the context of pressure-temperature (P-T) phase diagrams we plot liquid water (blue circle, c.f. Fig. 2), all terrestrial environs (orange circle, c.f. Fig. 3), and all inhabited terrestrial environments (green wedge, c.f. Fig. 4). From these plots we are able to identify where there is both Earth and liquid water (i.e. the intersection of the blue and orange circles) but where “No Life” has been discovered (Fig. 5).

Figure 1 is a sketch of our main goal: to identify the boundaries between “Life” and “No Life” in the regions of the Earth where water is liquid. To this end, Figure 2 presents water in several ways. The bulk of terrestrial ocean water is in the narrow vertical wedge. The dotted curves mark the phase space boundaries of “ocean salinity water”. Similarly, the solid curves mark our estimate of the “maximum liquid range”, i.e., the largest range of phase space that would be occupied by liquid water (fresh water, salt water, concentrated brines, thin films and super-heated water) on Earth, if the Earth had environments at the full range of temperatures and pressures shown. It does not; see Fig. 3. The melting curve of this “maximum” water has a freezing point depression of -89 °C at the triple point, probably due to a combination of thin film effects and high solute (e.g. dissolved salt) concentrations (Clark & Van Hart, 1981). Thin films of unfrozen water can exist at the contact between ice-ice or ice-soil grains at very low temperatures (Price 2000, Davis 2001 & Möhlmann 2008).

The most soluble common inorganic compounds in water have saturated aqueous molarities less than ~ 11 Molar (Lide, 2009). The magnitude of boiling point elevation due to the molality m of the solute is given by Raoult’s equation: \( \Delta T_b = K_b m \), where \( K_b \) is the ebullioscopic constant for water, 0.512 C/m (Silberberg & Duran, 2002) and m =
11, giving a boiling point elevation of 5.6 °C, which we use to make the thick vapour curve in Fig. 2.

**FIG. 2.** Pressure - temperature phase diagram for two types of water. The familiar vapor, sublimation and melting curves for ocean salinity water (3.5% salt by mass, dotted curves) is indistinguishable on this scale from pure water (Lide & Frederikse 1996). The dark vertical wedge represents the vast majority of the Earth’s oceans. We are concerned with the broadest range of pressures and temperatures under which water can remain liquid. This is labelled “Maximum liquid range” (solid curves). Due to increasing concentrations of solute and thin film effects at low temperatures, the coldest liquid water on Earth is -89 °C and has a triple point pressure of 3.2 x 10⁻⁷ bar (see Table 2, label E). For reference, the average global surface temperatures and pressures for Earth, Mars, Titan, Venus and at the top of Europa’s potential ocean are shown (see Table 1).

<table>
<thead>
<tr>
<th>Environment</th>
<th>Pressure [bar]</th>
<th>Temp. [°C]</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Earth surface</td>
<td>1</td>
<td>15</td>
<td>Dziewonski &amp; Anderson, 1981</td>
</tr>
<tr>
<td>Mars surface</td>
<td>0.06</td>
<td>-50</td>
<td>Barlow, 2008</td>
</tr>
<tr>
<td>Venus surface</td>
<td>93</td>
<td>480</td>
<td>Petculescu &amp; Lueptow, 2007</td>
</tr>
<tr>
<td>Titan surface</td>
<td>1.5</td>
<td>-180</td>
<td>Griffith et al., 2000</td>
</tr>
<tr>
<td>Top of Europa’s ocean</td>
<td>100</td>
<td>-3.9</td>
<td>Reynolds et al., 1983, Melosh et al., 2004</td>
</tr>
</tbody>
</table>
THE PRESSURE-TEMPERATURE PHASE DIAGRAM OF THE EARTH

Figure 3 is a pressure-temperature phase diagram of all terrestrial environments superimposed on the phase diagram of water from Fig. 2. Conceptually it is the same as the intersection of the blue and orange circles of Fig. 1: it shows the regions of phase space where there is both Earth and 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. The details of our Earth model including estimates of uncertainties are described in Appendix A. Although the phase diagram labelled “Maximum liquid range” is appropriate for the concentrated briny inclusions and thin liquid films in ice and permafrost on the Earth’s surface, the maximum freezing point depression for water on and in aerosols and organic particles in the Earth’s atmosphere will be intermediate between the “ocean salinity water” and “Maximum liquid range”.

**FIG 3. Superposition of terrestrial environments on the P-T diagram of water from Fig. 2.** The Earth’s core, mantle, crust and atmosphere are colored separately and are centered on the average geotherm(subsurface) and lapse rate( atmosphere). The ocean and crust geotherms meet at point “T”. A “Transient” region shows mantle that has intruded upwards (e.g. volcanism, geothermal vents). The horizontal thin line at 1 bar is the average sea level atmospheric pressure of the Earth. The parameters of our Earth model (e.g. core, mantle, continental crust, oceanic crust, geotherms and atmospheric lapse rates) are given in Appendix A. Extreme environments are listed and assigned a letter in Table 2, and are plotted here. For example, “C” and "D" represent the hottest and coldest days on the summit of Mt Everest. As in Fig. 2, the dark vertical wedge identifies the majority of ocean water. The green asterisk represents our estimate of the hottest and deepest water on Earth at T= 431°C and P = 3 x 10⁴ bar, corresponding to a depth of ~ 75 km.

**Table 2: Extreme Temperatures and Pressures In Earth’s Oceans and Crust**

<table>
<thead>
<tr>
<th>Key</th>
<th>Environment</th>
<th>Pressure [bar]</th>
<th>Temp [°C]</th>
<th>Reference</th>
</tr>
</thead>
</table>


<table>
<thead>
<tr>
<th>Key</th>
<th>Environment</th>
<th>Pressure [bar]</th>
<th>Temp [°C]</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Depth [km]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A</td>
<td>Surface lava e.g. Pahoehoe, rhyolite melt and basalt – hottest surface</td>
<td>0.4</td>
<td>1200</td>
<td>Harris et al., 1998</td>
</tr>
<tr>
<td></td>
<td>temperatures (Cotopaxi, Equador)</td>
<td>-5.897</td>
<td></td>
<td>Fagents &amp; Greeley, 2001</td>
</tr>
<tr>
<td></td>
<td></td>
<td>-2.293</td>
<td></td>
<td>Stein &amp; Spera, 2002</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Decker &amp; Decker, 1992</td>
</tr>
<tr>
<td>B</td>
<td>Thermal spring/vent (Pork Chop Geyser, Yellowstone, USA)</td>
<td>0.77</td>
<td>97</td>
<td>Guidry &amp; Chafetz, 2003</td>
</tr>
<tr>
<td>C,D</td>
<td>Mt Everest summit</td>
<td>0.33 ± 0.01</td>
<td>-74 to -26</td>
<td>Team Everest (2003) website</td>
</tr>
<tr>
<td></td>
<td></td>
<td>-8.848</td>
<td></td>
<td>West et al., 1983</td>
</tr>
<tr>
<td>E</td>
<td>Minimum land temperature (Vostok, Antarctica)</td>
<td>0.6</td>
<td>-89</td>
<td>National Oceanic and Atmospheric</td>
</tr>
<tr>
<td></td>
<td></td>
<td>-3.488</td>
<td></td>
<td>Administration (2007) website</td>
</tr>
<tr>
<td>F</td>
<td>Deep ice (South Pole, Antarctica)</td>
<td>72</td>
<td>-51</td>
<td>Price et al., 2002</td>
</tr>
<tr>
<td>G</td>
<td>Deep ice (Vostok, Antarctica)</td>
<td>2.5 x 10^2</td>
<td>-40</td>
<td>Abzyov et al., 1998</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2.75</td>
<td></td>
<td></td>
</tr>
<tr>
<td>H, K</td>
<td>Marianas trench (Challenger Deep)</td>
<td>1.32 x 10^3</td>
<td>2 to 300</td>
<td>Todo et al., 2005</td>
</tr>
<tr>
<td></td>
<td></td>
<td>10.896</td>
<td></td>
<td>The Mariana trench (2005) website</td>
</tr>
<tr>
<td>I</td>
<td>Mean base of oceanic crust</td>
<td>2.0 x 10^3</td>
<td>200</td>
<td>Lodders &amp; Fegley, 1998</td>
</tr>
<tr>
<td></td>
<td></td>
<td>10</td>
<td></td>
<td>Huppert &amp; Sparks, 1988</td>
</tr>
<tr>
<td>J</td>
<td>Crust mantle boundary – lowest temperature at thickest point (Himalaya,</td>
<td>5 x 10^4</td>
<td>500</td>
<td>Priestley et al., 2008</td>
</tr>
<tr>
<td></td>
<td>southern Tibet)</td>
<td>80</td>
<td></td>
<td></td>
</tr>
<tr>
<td>L</td>
<td>Sea floor hydrothermal vents – hottest (Mid-Atlantic ridge)</td>
<td>3.5 x 10^2</td>
<td>464</td>
<td>Koschinsky et al., 2008</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>M</td>
<td>Sea floor hydrothermal vents – hottest shallow</td>
<td>49</td>
<td>265</td>
<td>Stoffers et al., 2006</td>
</tr>
<tr>
<td></td>
<td>vents (Tonga arc)</td>
<td>0.54</td>
<td></td>
<td></td>
</tr>
<tr>
<td>N</td>
<td>Geothermal waters in the crust</td>
<td>28</td>
<td>157</td>
<td>Ellis &amp; Mahon, 1977</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>O</td>
<td>Lava lakes (Kilauea Iki, Hawaii; Eldfell volcano, Iceland)</td>
<td>10^2</td>
<td>1500</td>
<td>Helz &amp; Thornber, 1987</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.3</td>
<td></td>
<td>Jonsion &amp; Matthiasson, 1974</td>
</tr>
</tbody>
</table>

*Conversions between depth and pressure for atmosphere; land and water used the density values in Table A (Appendix A) and the formula: \( P(z) = P_0 + \rho g z \), where \( P(z) \) = pressure at depth \( z \); \( P_0 \) = normalizing pressure; \( \rho \) = density; \( g \) = gravitation acceleration. Gravitational acceleration values were taken from Dziewonski & Anderson (1981).

**THE PRESSURE-TEMPERATURE PHASE DIAGRAM OF TERRESTRIAL LIFE**

Figure 4 presents the phase space of life on Earth. We make a provisional distinction between active (green) and dormant (pale green) life. Although spores and other dormant life forms have evolved to withstand extreme environmental conditions, they could not complete their life cycles in those conditions. Examples of the extreme pressures (P) and temperatures (T) for active and dormant life are given in Tables 3 and 4 respectively (see also Appendix B). These environments include: (i) high P, high T, e.g. hydrothermal vents on the ocean floor; (ii) high P, low T, e.g. interstitial environments beneath thick ice sheets and (iii) low P, low T, e.g. Mt Everest; and (iv) low P, high T, e.g. warmest layers of the upper atmosphere.

In constructing these inhabited regions of phase space, we have assumed that the T < 122 °C upper limit to life (Takai et al., 2008) and that the T > -20 °C lower limit to active life (Junge et al., 2004) are both valid over a broader range of pressures than has been
fully explored by microbiologists. The pressure/pore-space relation and the link between barophilic and thermophilic adaptation is still unclear (Horikoshi, 1998, Garzón, 2004). Thus, our interpolations of the current high and low temperature limits for life in environments at pressures between \( \sim 1 \) and \( \sim 10^{2-3} \) bar should be viewed with caution. As a further indicator of caution, the current upper temperature limits of life (Takai et al 2008, Kashefi & Lovley 2003) are the results of a limited exploration of high T environments in hydrothermal vents. In the future, these limits will undoubtedly be higher and closer to the real limits of terrestrial life (Kelley et al 2007, Holden, Horsfeld et al 2006). In Fig. 4, the question mark and vertical dashed line at \( T = 250 \) °C emphasize this uncertainty.

**FIG. 4** Inhabited terrestrial environments superimposed on the P-T diagram of water from Fig. 2. Numbers 1-8 circumscribe our estimate of the region occupied by active terrestrial life (green) and are described in Table 3. Numbers 9-14 and the light green area represent our estimate of the region occupied by dormant terrestrial life and are described in Table 4. Atmospheric life is classified as dormant as most examples are spores and atmospheric non-spore-forming organisms have extremely low metabolic rates (Appendix B). The question mark and the yellow arrow pointing from the current upper temperature limit of life \( (T_{\text{life}} < 122 \) °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.

*Table 3. Active Life Environments*

<table>
<thead>
<tr>
<th>Key</th>
<th>Description</th>
<th>Pressure [bar]</th>
<th>Depth [km]</th>
<th>Temp [°C]</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Mt Everest summit</td>
<td>0.33 ± 0.01</td>
<td>-8.848</td>
<td>-20</td>
<td>Active microbial life has not been searched for at this location. We set 1 at the same minimum temperature at which active life has been found (see 8). Gangwar et al 2009 report life at -20 C at 5.6 km.</td>
</tr>
</tbody>
</table>
2 Thermal spring/vent (Pork Chop Geyser, Yellowstone National Park, USA) 0.77 97 Guidry & Chafetz, 2003 (Lilypad stromatolites)

3 Shallow hydrothermal vents 2 122 Thermophilic life has not been searched for at this location. Life could exist in this environment, as the maximum temperature for life found thus far is 122°C (see 4) and vents at this depth can exceed 122°C and life has been found near vents at 40-100°C in this environment (Prol-Ledesma, 2003). We have therefore placed this marker at a temperature of 122°C.

4 Ocean hydrothermal vent where highest temperature life found (Finn Vent, Mothra field, Pacific Ocean) 2.1 x 10² 2.27 122 Takai et al. (2008) and Kashfi & Lovley, 2003 (Archaea, closely related to closely related to Pyrodictium occultum Pyrobaculum Aerophilum) Shrenk et al., 2003

5 Marianas trench, deepest part of ocean (Challenger Deep, Pacific Ocean) 1.32 x 10³ 10.924 122 Thermophilic life has not been searched for at this location. Life could exist in this environment, as the maximum temperature for life found thus far is 122°C (see marker 4) and vents at this depth can exceed 122°C (The Mariana Trench, 2003 website) and life has been found at 2-3 °C temperatures in this environment (Todo et al., 2005). We have therefore placed this marker at a temperature of 122°C.

6 Deepest active life in crust from borehole (Gravberg, Sweden) 1.55 x 10³ 5.278 75 Szewzyk & Szewzyk, 1994 (Thermoanaerobacte, Thermoanaerobium, Clostridium, close relationship to Clostridium thermohydrosulfuricum)

7 Marianas trench (Challenger Deep, Pacific Ocean) 1.32 x 10³ 10.896 2 Todo et al., 2005; Takami et al., 1997 (Foraminifera: Lagenammina, Nodellum, Resigella)

8 Arctic Ice core, lowest temperature active life. 10² 2.75 -20 Junge et al., 2004 (Bacteria (EUB338), Cytophaga-Flavobacteria (CF319a), Archaea (ARCH915)

Table 4. Dormant Life Environments

<table>
<thead>
<tr>
<th>Key</th>
<th>Description</th>
<th>Pressure [bar] Depth [km]</th>
<th>Temp [°C]</th>
<th>Reference</th>
<th>Metabolic activity</th>
</tr>
</thead>
<tbody>
<tr>
<td>9</td>
<td>Vostok ice core life</td>
<td>10² 2.75</td>
<td>-40</td>
<td>Abyzov et al., 1998 Price &amp; Sowers, 2004</td>
<td>Cell activity after incubation; interpreted as cells in situ were able to maintain vital functions but not reproduce</td>
</tr>
<tr>
<td>10</td>
<td>Greenland open mine life</td>
<td>1</td>
<td>-30</td>
<td>Langdahl &amp; Ingvorsen, 1997</td>
<td>Sampled at warmer temperatures so metabolic activity at low temperature limit is unknown (Thiobacillus ferroxidans, Thiobacillus thiooxidans and Leptospirillum ferroxidans)</td>
</tr>
<tr>
<td>11</td>
<td>Mt Everest summit</td>
<td>0.33 ± 0.01 -8.848</td>
<td>-40</td>
<td></td>
<td>Marker 11 is at the minimum temperature at which dormant microbial life has been found in the crust in the presence of liquid water (see 9); and the pressure is given by 1.</td>
</tr>
<tr>
<td>12</td>
<td>Bacterial spores</td>
<td>0.0025*</td>
<td>-20*</td>
<td>Wainwright et al.,</td>
<td>Dormant (spore) in atmosphere but cultured in laboratory</td>
</tr>
</tbody>
</table>
(atmosphere)  -41  2002  (Bacillus simplex, Staphylococcus asteuri, Engyodontium album)

13 Non-spore forming eubacteria (atmosphere)  0.0553* -20  Griffin, 2008  Growth after extended incubation (Micrococcaceae, Microbacteriaceae, Brevibacterium Luteolum, Staphylococcus)

14 Bacterial spores (atmosphere)  0.00002* -77  Imshenetsky et al., 1978  Dormant (spore) in atmosphere (Circinella muscae, Aspergillus niger, Papulaspora anomala, Penicillium notatum, Mycobacterium luteum, Micrococcus albus)

*Temperature and pressure from Hewitt & Jackson (2003).

**FIG. 5. Superposition of inhabited environments from Fig. 4 and the terrestrial environments from Fig. 3. on the P-T diagram of water from Fig. 2.** 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.

**Results**

Fig. 5 can be used to quantify the potential limits of the terrestrial biosphere. For example, we can compute what fraction of the volume of the Earth is inhabited. The radius of the Earth $r_e = 6378$ km. The biosphere extends for ~ 10 km above this (e.g. throughout the troposphere, on top of mountains) and extends for ~10 km down in the oceans and about 5 km down into continental crust (see Table 3, “6” and “7”). Assuming oceans occupy 70% of the surface and continents 30%, the biosphere occupies ~ 1% of the volume of the Earth (the 10 km thick troposphere is included in the volume of the
Earth). Thus, after 4 billion years of evolution, the terrestrial biosphere has been unable to extend into ~99% of the volume of the Earth.

We would also like to know: What fraction of the volume of the Earth where liquid water exists, is known to host life? The computation is analogous to that above except instead of the denominator in the ratio being the volume of the entire Earth, it is the volume of the shell of the Earth that contains liquid water. The thickness of such a shell extends to depth of ~75 km and is marked by the green asterisk in Fig. 5. Here we ignore the atmosphere and 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.

We can obtain analogous results for the area in phase space [log P log T] in Fig. 5 by asking: What fraction of the phase space area of the Earth where liquid water exists, is known to host life? In terms of Fig. 5, this question becomes, what fraction of the yellow area that overlies the blue area, is occupied by green (active or dormant life). Here, for simplicity, we exclude the atmosphere since it is not clear that liquid water droplets and films on aerosols extend over the full “maximum liquid range”. The computation of the relevant areas yields the result that ~36% of the phase area occupied by terrestrial water has been found to host life. ~30% is occupied by active life and the remaining ~6% by dormant life. Thus, 64% of the phase space of terrestrial water and 88% of the volume of the Earth containing water, is not known to harbor life. There are many liquid water environments on Earth that, as far as we know, do not host life. If the known limits of life do not require large modifications, these limits represent a significant constraint on the biosphere since ~4 billion years of evolution have not allowed life to adapt to the 64% of P-T phase space and 88% of the volume of the Earth where liquid water exists.

**SUMMARY AND DISCUSSION**

We have made an empirical description of the phase space and volumetric limits of terrestrial life. Plausible reasons for these limits are combinations of temperature, water activity, energy and nutrient availability and pore space. However, determining how these factors combine to prevent life will be a challenging part of future extremophilic research.

Our analysis can be summarized as follows:

(i) High pressure limit to life
   Fig. 5 suggests that the apparent high pressure limit of life is a selection effect since life has been found at the maximum depths at which it has been searched for.

(ii) High temperature limit to life
   The current high temperature limit for life is 122 °C. This limit cannot be verified as there is a substantial amount of liquid water (~ 1% of the total terrestrial liquid volume) at higher temperatures that has not been fully searched for life. If 122 °C is a real limit, this indicates a severe restriction of the terrestrial biosphere, where only ~12% of the volume of Earth that
has liquid water, supports life. If the high temperature limit for life is increased to 250 °C, the thickness of the biosphere would approximately triple to include ~38% of the volume of the Earth that has liquid water.

(iii) Low temperature limit to life
The current low temperature limit for life is -20 °C. There are thin films of liquid water and potentially briny liquid water that can remain liquid, at lower temperatures with a water activity above the proposed limit of 0.6 for life (Grant 2004). If low water activity is a fundamental limit, rather than low temperature, then active life may occur in water temperatures down to at least -30°C due the presence of brines. A substantial volume of terrestrial liquid water (> 1.5 x 10^7 km^3) exists in permafrost and a large fraction of this would persist through temperatures below -20 °C. It would be significant if life was found to be excluded from these liquid water sources.

(iv) Low pressure limit to life
All examples of life found at pressures less than 0.3 bar have been classified as dormant. A low pressure limit for life may be due to temperature, water activity or nutrient limits at these altitudes. Liquid water would most likely exist as a thin film on aerosols or organic particles in the atmosphere.

Our phase diagrams can be used to refine and focus searches for life on Earth and elsewhere. Our analysis highlights the need to look for environments that have conditions at the extreme limits known for life, to quantify the extent to which terrestrial life follows the water. Current limits indicate that the terrestrial biosphere inhabits only a small subset of the full range of liquid water environments on Earth. More work needs to be done to determine how much of the apparently uninhabited water appears that way due to the difficulty and incompleteness of the observations.
### Appendix A  Details of the Earth Model shown in Fig. 3

#### TABLE A  Model parameters for the Earth’s core, mantle, crust and atmosphere.

**Core**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Range</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density (kg m$^{-3}$)</td>
<td>$1.3 \times 10^4$ (averaged over inner and outer core)</td>
<td>Dziewonski &amp; Anderson, 1981, Lodders &amp; Fegley, 1998</td>
</tr>
<tr>
<td>Mean pressure gradient (Pa km$^{-1}$)</td>
<td>$1.27 \times 10^5$</td>
<td>Dziewonski &amp; Anderson, 1981, Lodders &amp; Fegley, 1998</td>
</tr>
<tr>
<td>Geothermal gradient (K km$^{-1}$)</td>
<td>0.6-0.9; our model 0.85</td>
<td>Ernst, 1990, Saxena et al., 1994, Karato (2003)</td>
</tr>
</tbody>
</table>

**Mantle**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Range</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density (kg m$^{-3}$)</td>
<td>$4.5 \times 10^3$</td>
<td>Mason, 1958</td>
</tr>
<tr>
<td>Mean pressure gradient (Pa km$^{-1}$)</td>
<td>$4.41 \times 10^4$</td>
<td>Dziewonski &amp; Anderson, 1981, Lodders &amp; Fegley, 1998</td>
</tr>
<tr>
<td>Geothermal gradient (K km$^{-1}$)</td>
<td>0.3-1; our model 0.7</td>
<td>Mason, 1958, Schiano et al. (2006)</td>
</tr>
</tbody>
</table>

**Continental crust**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Range</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature (K)</td>
<td>$184-331$ (surface)</td>
<td>Lodders &amp; Fegley, 1998</td>
</tr>
<tr>
<td>Pressure (bar)</td>
<td>$\sim 800$ (average base temp; magma)</td>
<td>Huppert &amp; Sparks, 1988</td>
</tr>
<tr>
<td>Density (km$^{-3}$)</td>
<td>$2.8 \times 10^3$</td>
<td>Lodders &amp; Fegley, 1998, Lodders &amp; Fegley, 1998</td>
</tr>
<tr>
<td>Mean pressure gradient (Pa km$^{-1}$)</td>
<td>$2.74 \times 10^4$</td>
<td>Dziewonski &amp; Anderson, 1981</td>
</tr>
<tr>
<td>Geothermal gradient (K km$^{-1}$)</td>
<td>25 (mean)</td>
<td>Scheidegger, 1982</td>
</tr>
</tbody>
</table>

**Oceanic crust**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Range</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure (bar)</td>
<td>$4 \times 10^2$ (base ocean) – $1.9 \times 10^1$ (Moho)</td>
<td>Lodders &amp; Fegley, 1998, Dziewonski &amp; Anderson, 1981</td>
</tr>
<tr>
<td>Thickness (km)</td>
<td>5 (mean oceanic)</td>
<td></td>
</tr>
</tbody>
</table>
### Mean pressure gradient (Pa km⁻¹)

<table>
<thead>
<tr>
<th>Value</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>4 - 20</td>
<td>(range)</td>
</tr>
<tr>
<td>4</td>
<td>(mean depth under ocean)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Value</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.94 × 10⁴</td>
<td></td>
</tr>
</tbody>
</table>

### Density (kg m⁻³)

<table>
<thead>
<tr>
<th>Value</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>3 × 10³</td>
<td></td>
</tr>
</tbody>
</table>

### Geothermal gradient (K km⁻¹)

<table>
<thead>
<tr>
<th>Value</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>40</td>
<td></td>
</tr>
</tbody>
</table>

## Atmosphere

### Mean lapse rate temperature (K km⁻¹)

<table>
<thead>
<tr>
<th>Value</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.5</td>
<td>troposphere</td>
</tr>
<tr>
<td>-2.0</td>
<td>stratosphere</td>
</tr>
<tr>
<td>2.6</td>
<td>mesosphere</td>
</tr>
<tr>
<td>-5.8</td>
<td>thermosphere</td>
</tr>
</tbody>
</table>

### Lapse rate pressure (Pa km⁻¹)

<table>
<thead>
<tr>
<th>Value</th>
<th>Equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\frac{-0.0012(1 - \frac{z}{44307.69})}{4.26})</td>
<td>below 86 km</td>
</tr>
</tbody>
</table>

*Temperature lapse rate \(\Gamma_t\) is the rate of decrease of temperature with height: \(\Gamma_t(z) = -\frac{dT}{dz}\)

*Pressure lapse rate \(\Gamma_p\) is the rate of decrease of pressure with height: \(\Gamma_p(z) = \frac{dP}{dz}\) using the equation:

\[ z = \left[ 1 - \left(\frac{P}{10.13\times10^5}\right)^{0.15} \right] \times 44307.69 \text{ where } z = \text{altitude (km)} \text{ and } P = \text{static pressure (Pa) (US Standard Atmosphere, 1976)} \]

## Core

The Earth’s core extends from a depth of 2890 km to 6378 km. At the centre the pressure is modelled as 3.6 × 10⁶ bar (Dziewonski & Anderson, 1981; Davies, 1999). As the core density is not well constrained from seismic models there is a range of estimates for the central core pressure between 2.8 – 3.8 × 10⁶ bar (Fowler, 1990; Lodders & Fegley, 1998). Similarly we have chosen a representative pressure value for the core-mantle boundary (CMB) of 1.4 × 10⁶ bar (Davies, 1999) within the range of 0.6 - 3.2 × 10⁶ bar (Fowler, 1990; Lodders & Fegley, 1998; Davies, 1999). The pressure value for the CMB is not essential for our model as the transition from core to mantle occurs within a layer ~40 km thick (Doornbos, 1983; Williams & Garnero, 1996). At its central depth the core temperature is taken in our model to be 5700 K (Fowler, 1990).

Temperature models for the core are dependent on core composition and estimates for the central temperature range widely from 3800-6800 K (Jeanloz, 1990; Davies, 1999). Similarly with the CMB we have chosen a representative temperature of 2700 K (Davies, 1999) within the range of estimates 1700-4500 K (Jeanloz, 1990; Decker & Decker, 1992; Stein & Wyssession, 2003). As stated above the core-mantle boundary is thought to be a ~40 km thermal boundary layer, with an estimated radial temperature increase of 800 K (Stacey & Loper, 1984) across it. Melting temperatures for the assumed core composition are pressure dependent (Andersen et al., 2002) however our chosen boundary values and geotherm of 0.85 K km⁻¹ leads to a liquid outer region of the core and a solid inner region (from the solidus of Jeanloz, 1990). This is consistent with recent models (Stein & Wyssession, 2003). The central core may be liquid if its temperature exceeds 5120 K (Nakagawa & Tackley, 2004).

The range of estimates of pressure and temperature conditions in the inner core are represented through vertical and horizontal error bars that encompass the range of estimates in the literature. The same holds for estimates of conditions across the core to mantle transition.

### Mantle and transient

The Earth’s mantle extends from a depth of 2890 km at the core-mantle boundary to a range of 4-80 km beneath oceanic and continental crust. Our chosen average of the
Mohorovičić discontinuity (Mohorovičić, 1909) is 3.3 x 10³ bar and 800 K, consistent
with the average continental crustal depth of 35 km (Lodders & Fegley 1998). The
variation in the Moho will be discussed in more detail below. Our CMB boundary values
lead to a modelled mantle geotherm of 0.66 K km⁻¹. This temperature profile lies below
the assumed mantle solidus (Nakagawa & Tackley, 2004; Zerr, 1998) resulting in the
expected solid mantle (Stein & Wysession, 2003). For example, the solidus temperature
at the CMB pressure is estimated as 4300K (Nakagawa & Tackley, 2004).

There are ‘short-term’ environments which are initially at typical mantle temperatures
but are at crustal pressures. We have classified these environments as ‘transient’. They
include magma chambers in the crust, surface lava and subsurface lava lakes (Helz &
Thornber, 1987; Jonsson & Matthiasson, 1974). Over time scales of decades the
majority of these environments (Oppenheimer & Francis, 1998) will cool along a
constant pressure line to lie within the crustal region (see Figure 3).

**Crust and surface**
The thickness of the crust varies widely - between 5 to around 80 km (Pavlenkova &
Zverev, 1981; Holbig & Grove, 2008) beneath continental crust (averaging 35 km), and
only from 2 to 10 km under oceanic crust (averaging 5-7 km). The global average depth
is 19 km (Dziewonski & Anderson, 1981). As the Moho marks a density transition it
does not have a fixed pressure or temperature. Shallow Moho (beneath thin crust) is
typically quite cool due to its lower heat flow. A large fraction of the crust is <40 km
thick (Mooney et al., 1998) and lies above mantle cooler than 800 K (Blackwell, 1971).
With increasing depth the temperature of the crust and Moho typically increases due to
increasing heat flow. Deep Moho beneath thick crust can however be cool, with the
current range of deep Moho temperatures being ~800 K (Hyndman et al., 2005) to 1400
K (Jiménez-Munt et al., 2009). Taking a typical average continental crustal density the
80 km deep Moho (Sokolova et al., 1978) lies at a pressure of around 20 kPa – roughly
an order of magnitude greater than the pressure at shallow Moho. Due to these large
variations in pressure and temperature at the base of the crust there is difficulty in
representing this boundary simply on a P-T diagram. We have chosen to mark the
average conditions at the base of average thickness continental and oceanic crust, and
to use error bars to encompass the range of crustal thickness (pressures) and the
variation in temperature at different Moho depths. A sloped error bar is due to the
general trend of deeper Moho being at higher temperature.

A more fundamental consideration is the Earth’s heat flow, not explicitly represented
in our model. The Earth’s surface heat flow varies predominantly between 40-85 mWm⁻²
(Pollack & Chapman, 1977) with an average of ~55 mWm⁻². The heat flow from the
Moho beneath the continents is fairly fixed at around 25 mWm⁻² (Čermák et al,1989)
with the discrepancy made up from radiogenic heat production from elements within
the crust. There is less radiogenic heat production in the oceanic crust itself (Smith,
1973) and thus its heat flow shows much less variation and has an average of 100
mWm² (Sclater & Francheteau, 1970; Davies, 1999). The crustal heat flow and the
thermal conductivity of crustal materials together determine the subsurface geotherm,
through the relation:

\[
\frac{\partial T}{\partial z} = \frac{Q}{k}
\]
Where $\frac{\partial T}{\partial z}$ is the geotherm (K km$^{-1}$); Q = heat flow (mWm$^{-2}$) and k = thermal conductivity (Wm$^{-1}$K$^{-1}$). Hence this heterogeneity in heat flow (and of course crustal materials) has the consequence that temperatures can still show large regional variation many kilometres beneath the subsurface (Artemieva, 2006) which can continue even into the asthenosphere (Smith, 1973). Thus oceanic and continental geotherms cannot be guaranteed convergence until below $\sim$200 km in the asthenosphere where convective heat transfer dominates (Andersen, 1979; Chapman, 1986). In our model the oceanic and continental geotherms converge at $\sim$10 km into the continental crust. A typical geothermal gradient in the oceanic crust is $\sim$35 K km$^{-1}$ (100 mWm$^2$ heat flow; thermal conductivity for basalt of 3 Wm$^{-1}$K$^{-1}$ from Clauser & Huenges, 1995). The mean continental geotherm is 25 K km$^{-1}$ (Scheidegger, 1976) however it ranges greatly due to variations in heat flow (10-130 mWm$^2$ at the surface) and thermal conductivity of rock (0.5 – 7 Wm$^{-1}$K$^{-1}$ range: Clauser & Huenges, 1995), and is predominantly between 5-70 K km$^{-1}$ (Chapman & Pollack, 1975).

The extreme environments of the Earth are given in Table 2. All known environments in the crust, oceans and surface lie within the pressure-temperature polygon and within the range of the error bars on the average geotherm. The mean continental crustal geotherm shown, averaged over 35 km of crust, is 15 K km$^{-1}$. The brown shaded region accommodates much steeper geotherms (up to $\sim$80 K km$^{-1}$) and so is consistent with the range of true geothermal gradients on Earth.

Appendix B Explanatory Details for Tables 3 and 4.

Life has been found throughout the Earth’s atmosphere, to an altitude of 77 km above the surface (Imshenetsky et al., 1978). These organisms can be classified into two types – spore or spore forming bacteria (eg. Bacillus simplex; Wainwright et al., 2002); and bacteria that do not form spores (eg. Micrococcus; Griffin, 2008). This classification is made here as it allows for a distinction to be made between active and potentially dormant life in the atmosphere. Spore structures allow bacteria to survive for extended periods of time in unfavourable conditions. This means that spores collected from the atmosphere can be dormant and yet viable, and so may be able to be cultivated in the laboratory. It is unclear however whether such spores were actively metabolizing, be it at a very slow rate, in atmospheric conditions (personal correspondence, Dr Yogesh Shouche, Fri, April 3, 2009). Non-spore forming bacteria that are retrieved from the atmosphere, however, are thought to have been active in that environment if they are able to be grown in the laboratory. Using this distinction, some have concluded that active life has been isolated from an altitude of 20 km in the Earth’s atmosphere (Griffin, 2008), at an ambient pressure and temperature of 0.055 bar and -56 °C respectively. This appears to extend the lower temperature limit of life, however the result should be viewed with caution as no measurements of metabolism were made. Other species of non-spore forming bacteria have been isolated from the atmosphere at higher altitudes and warmer temperatures (between 20-70 km altitude) but have been found to be viable yet non-culturable (Wainwright et al., 2004) and are examples of dormant life. The current upper boundary of the biosphere (most likely at the tropopause at $\sim$10 km altitude which is a boundary to the vertical movement of particles; Wainwright et al.,
2006) lies at 77m (ambient pressure and temperature of ~ 10^-5 bar, -70 °C respectively) where spores (eg., Circinella muscae) were isolated (Imschenetsky et al., 1978) and were most likely dormant at in situ conditions. Examples of the potentially lowest temperature, active life and the highest altitude (dormant) life are included our life regime in Figure 4.

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