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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 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. Eighty-eight percent of the volume of Earth where liquid water exists is not known to host life. This potentially uninhabited terrestrial liquid water includes i) hot and deep regions of Earth where some combination of high temperature ($T > 122^{\circ}\text{C}$) and restrictions on pore space, nutrients, and energy is the limiting factor, and ii) cold and near surface regions of Earth, such as brine inclusions and thin films in ice and permafrost (depths less than ~ 1 km), where low temperatures ($T < -40^{\circ}\text{C}$), low water activity ($a_w < 0.6$), or both 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 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) described 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 or comprehensively described where these wet uninhabitable environments are. To this end, we have developed a model for presenting Earth and Mars on a pressure-temperature (P-T) diagram (see Jones & Lineweaver, 2008). See Table 1 for the surface P-T conditions of solar system bodies.

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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 environments (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 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”, that is, 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 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 $-89\text{ }^{\circ}\text{C}$ 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, $0.512\text{ }^{\circ}\text{C/m}$ (Silberberg & Duran, 2002), and $m = 11$, giving a boiling point elevation of $5.6\text{ }^{\circ}\text{C}$, which we use to make the thick vapor 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 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 3.2×10^{-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 1. :Average pressures and temperatures on some solar system bodies

Environment	Pressure [bar]	Temp. [°C]	Reference
Earth surface	1	15	Dziewonski & Anderson, 1981
Mars surface	0.06	-50	Barlow, 2008
Venus surface	93	480	Petculescu & Lueptow, 2007
Titan surface	1.5	-180	Griffith <i>et al.</i> , 2000
Top of Europa's ocean	100	-3.9	Reynolds <i>et al.</i> , 1983 Melosh <i>et al.</i> , 2004

THE PRESSURE-TEMPERATURE PHASE DIAGRAM OF 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 Table 2 and Appendix A Table A. The subsurface pressure and temperature gradients of Earth are proportional to each other and are related through density, conductivity, and heat production. This limits the P-T space occupied by Earth. Although the phase diagram labelled “Maximum liquid range” is appropriate for the concentrated briny inclusions and thin liquid films in ice and permafrost on Earth’s surface, the maximum freezing point depression for water on, and in, aerosols and organic particles in Earth’s atmosphere will be intermediate between the “ocean salinity water” and “Maximum liquid range.” The phase models in Figs. 3 and 5 include short-term environments that are temporarily at typical mantle temperatures but are at crustal pressures. We have labeled these environments as “Transient” in Fig. 3. 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. The size of the area occupied by Earth in the P-T space of Fig. 5 is determined by a combination of uncertainty in geothermal gradients and variations (both spatial and temporal) in geotherms. Thus, we have attempted to include the dynamic nature of Earth in the model by making the shaded Earth region wide enough to include cycling of pressures and temperatures. For example, in Fig. 3 the temperature at the summit of Mount Everest varies between the maximum (point C) and minimum (point D), and atmospheric pressures and temperatures vary within the pink shaded region around the average atmospheric geotherm. Also in Fig. 3 the transient permeation of liquid water to depths of at least 6 km in the crust through permeable rock-cracking (Sleep & Zoback, 2007) is included, as the average crust geotherm (the solid black line) allows liquid water in the crust to a depth of ~ 30 km. The shallowest crustal geotherm allows liquid water in the crust to a depth of ~ 75 km (green asterisk in Fig. 3). In Fig. 4 the maximum depth of the biosphere is currently determined by the depth of the 122 °C isotherm – the depth of which varies with crustal

characteristics such as heat flow and thermal conductivity. From Fig. 3, the 122 °C isotherm varies between the surface and a maximum depth of ~ 20 km (along a cool geotherm) in crust.

FIG 3. Superposition of terrestrial environments on the P-T diagram of water from Fig. 2. Earth's core, mantle, crust, and atmosphere are colored separately and centered on the average geotherm(subsurface) and lapse rate(atmosphere). The ocean and crust geotherms meet at point "I." 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 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 they 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 $T = 431^{\circ}\text{C}$ and $P = 3 \times 10^4$ bar, corresponding to a depth of ~ 75 km.

Table 2.: Extreme Temperatures and Pressures In Earth's Oceans and Crust

Key	Environment	Pressure [bar] Depth [km]	Temp [°C]	Reference
A	Surface lava e.g. Pahoehoe, rhyolite melt and basalt – hottest surface temperatures (Cotopaxi, Equador)	0.4 -5.897	1200	Harris <i>et al.</i> , 1998 Fagents & Greeley, 2001 Stein & Spera, 2002 Decker & Decker, 1992
B	Thermal spring/vent (Pork Chop Geyser, Yellowstone, USA)	0.77 -2.293	97	Guidry & Chafetz, 2003
C,D	Mt Everest summit	0.33 ± 0.01 -8.848	-74 to - 26	Team Everest (2003) website West <i>et al.</i> , 1983
E	Minimum land temperature (Vostok, Antarctica)	0.6 -3.488	-89	National Oceanic and Atmospheric Administration (2007) website
F	Deep ice (South Pole, Antarctica)	72 0.8	-51	Price <i>et al.</i> , 2002
G	Deep ice (Vostok, Antarctica)	2.5 x 10 ² 2.75	-40	Abyzov <i>et al.</i> , 1998
H, K	Marianas trench (Challenger Deep)	1.32 x 10 ³ 10.896	2 to 300	Todo <i>et al.</i> , 2005 The Mariana trench (2003) website
I	Mean base of oceanic crust	2.0 x 10 ³ 10	200	Lodders & Fegley, 1998 Huppert & Sparks, 1988
J	Crust mantle boundary – lowest temperature at thickest point (Himalaya, southern Tibet)	5 x 10 ⁴ 80	500	Priestley <i>et al.</i> , 2008
L	Sea floor hydrothermal vents – hottest (Mid-Atlantic ridge)	3.5 x 10 ² 3	464	Koschinsky <i>et al.</i> , 2008
M	Sea floor hydrothermal vents – hottest shallow vents (Tonga arc)	49 0.54	265	Stoffers <i>et al.</i> , 2006
N	Geothermal waters in the crust	28 0.1	157	Ellis & Mahon, 1977
O	Lava lakes (Kilauea Iki, Hawaii; Eldfell volcano, Iceland)	10 ² 0.3	1500	Helz & Thornber, 1987 Jonsson & Matthiasson, 1974

*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; ρ = 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); (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 assumed that the $T < 122$ °C upper limit to life (Takai *et al.*, 2008) and 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 ~ 1 and $\sim 10^{2-3}$ bar should be viewed with caution. As a further indicator of caution, the currently believed 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 2008, Horsfeld *et al.* 2006). In Fig. 4, the question mark and vertical dashed line at $T = 250$ °C emphasize this uncertainty. Furthermore, in the atmosphere in Figs. 3 and 5, the existence of liquid water environments are transient. Due to the movement of air currents and the relationship between atmosphere and surface, there are no continual liquid water environments at low pressures. For example, at the triple point of “ocean salinity water” in Fig. 3 at ~ 25 km altitude, the conditions may be dry even though liquid water is stable.

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 that have extremely low metabolic rates (Appendix B). The question mark and the yellow arrow pointing from the current upper temperature limit of life ($T_{\text{life}} < 122\text{ }^{\circ}\text{C}$) to the vertical dashed yellow line at $T = 250\text{ }^{\circ}\text{C}$ represents the change that would occur in this diagram if life were found at $T = 250\text{ }^{\circ}\text{C}$.

Table 3. Active Life Environments

Key	Description	Pressure [bar] Depth [km]	Temp [$^{\circ}\text{C}$]	Reference
1	Mt Everest summit	0.33 ± 0.01 -8.848	-20	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.
2	Thermal spring/vent (Pork Chop Geyser, Yellowstone National Park,	0.77 -2.293	97	Guidry & Chafetz, 2003 (<i>Lilypad stromatolites</i>)

3	USA) Shallow hydrothermal vents	2 0.01	122	Thermophilic life has been found in shallow vents at temperatures between 40-100 °C (Amend <i>et al.</i> , 2003; Prol-Ledesma, 2003; Stetter, 2006). Life has not been found at the maximum temperature of 122 °C (see 4) however temperatures of vents at this depth can exceed 122 °C (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)	2.1×10^2 2.27	122	Takai <i>et al.</i> (2008) and Kashefi & Lovley, 2003 (<i>Archaea</i> , closely related to <i>Pyrodictium occultum</i> <i>Pyrobaculum Aerophilum</i>) Schrenk <i>et al.</i> , 2003
5	Marianas trench, deepest part of ocean (Challenger Deep, Pacific Ocean)	1.32×10^3 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 <i>et al.</i> , 2005). We have therefore placed this marker at a temperature of 122°C.
6	Deepest active life in crust from borehole (Gravberg, Sweden)	1.55×10^3 5.278	75	Szewzyk & Szewzyk, 1994 (<i>Thermoanaerobacte</i> , <i>Thermoanaerobium</i> , <i>Clostridium</i> , close relationship to <i>Clostridium thermohydrosulfuricum</i>)
7	Marianas trench (Challenger Deep, Pacific Ocean)	1.32×10^3 10.896	2	Todo <i>et al.</i> , 2005; Takami <i>et al.</i> , 1997 (<i>Foraminifera</i> : <i>Lagenammina</i> , <i>Nodellum</i> , <i>Resigella</i>)
8	Arctic Ice core, lowest temperature active life.	10^2 2.75	-20	Junge <i>et al.</i> , 2004 (<i>Bacteria</i> (EUB338), <i>Cytophaga-Flavobacteria</i> (CF319a), <i>Archaea</i> (ARCH915))

Table 4. Dormant Life Environments

Key	Description	Pressure [bar] Depth [km]	Temp [°C]	Reference	Metabolic activity
9	Vostok ice core life	10 ² 2.75	-40	Abyzov <i>et al.</i> , 1998 Price & Sowers, 2004	Cell activity after incubation; interpreted as cells in situ were able to maintain vital functions but not reproduce
10	Greenland open mine life	1	-30	Langdahl & Ingvorsen, 1997	Sampled at warmer temperatures so metabolic activity at low temperature limit is unknown (<i>Thiobacillus ferrooxidans</i> , <i>Thiobacillus thiooxidans</i> and <i>Leptospirillum ferrooxidans</i>)
11	Mt Everest summit	0.33 ± 0.01 -8.848	-40		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 .
12	Bacterial spores (atmosphere)	0.0553* -20	-20*	Wainwright <i>et al.</i> , 2002	Dormant (spore) in atmosphere but cultured in laboratory (<i>Bacillus simplex</i> , <i>Staphylococcus asteuri</i> , <i>Engyodontium album</i>)
13	Non-spore forming eubacteria (atmosphere)	0.0025* -41	-56*	Griffin, 2008	Growth after extended incubation (<i>Micrococcaceae</i> , <i>Microbacteriaceae</i> , <i>Brevibacterium Luteolum</i> , <i>Staphylococcus</i>)
14	Bacterial spores (atmosphere)	0.00002* -77	-69*	Imshenetsky <i>et al.</i> , 1978	Dormant (spore) in atmosphere (<i>Circinella muscae</i> , <i>Aspergillus niger</i> , <i>Papulaspora anomala</i> , <i>Penicillium notatum</i> , <i>Mycobacterium luteum</i> , <i>Micrococcus albus</i>)

*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 thought to be 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 Earth is inhabited. The radius of 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 occupy 30%, the biosphere occupies ~ 1% of the volume of Earth (the 10 km thick troposphere is included in the volume of Earth). Thus, after 4 billion years of evolution, the terrestrial biosphere seems to have been unable to extend into ~99% of the volume of Earth.

Also of interest is what fraction of the volume of 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 Earth that contains liquid water. The thickness of such a shell extends to a 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 Earth where liquid water exists is known to host life.

Thus, according to our current state of exploration, 88% of the volume of 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 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. Approximately 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 Earth containing water are 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 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 for which it has been searched. This conclusion is supported by experimental studies in which barophiles were taken to those pressures encountered deep within the crust and it was found that the organisms remained alive and viable (Margosch *et al.*, 2006 for pressures consistent with ~50 km crustal depth; Sharma *et al.* 2002 for pressures at ~35 km depth).

(ii) High temperature limit to life

The currently held 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 Earth that has liquid water. However, see Wiersberg & Erzinger, 2008 and Ellsworth *et al.*, 2005 for indications that hyperthermophiles – specifically methanogens- are limited to $T < 135$ °C.

(iii) Low temperature limit to life

The currently held 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 ($> 1.5 \times 10^7 \text{ km}^3$) exists in permafrost, and a large fraction of this would persist through temperatures below -20°C . It would be significant if life were 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; however, its existence in low pressure environments is transient.

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 so as 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.

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Appendix A Details of the Earth Model shown in Fig. 3

TABLE A Model parameters for Earth's core, mantle, crust and atmosphere.

Core		
	Range	Reference
Temperature (K)	2700^{+1800}_{-1000} (outer) – 5700^{+1100}_{-1900} (inner)	Fowler, 1990 Jeanloz, 1990 Lodders & Fegley, 1998 Davies, 1999
Pressure (bar)	$1.39^{+1.81}_{+0.23} - 0.76 \times 10^6$ (outer) – $3.57 - 0.77 \times 10^6$ (inner)	Fowler, 1990 Lodders & Fegley, 1998 Davies, 1999 Dziewonski & Anderson, 1981
Depth (km)	2890 – 6378	Dziewonski & Anderson, 1981 Lodders & Fegley, 1998
Density (kg m^{-3})	1.3×10^4 (averaged over inner and outer core)	Dziewonski & Anderson, 1981 Lodders & Fegley, 1998
Mean pressure gradient (Pa km^{-1})	1.27×10^5	Lodders & Fegley, 1998 Dziewonski & Anderson, 1981
Geothermal gradient (K km^{-1})	0.6-0.9; our model 0.85	Ernst, 1990 Saxena <i>et al.</i> , 1994 Karato (2003)
Mantle		
Temperature (K)	800^{+1380}_{-1000} (outer) – 2700^{+1800}_{-1000} (CMB)	Fowler, 1990 Lodders & Fegley, 1998 Davies, 1999
Pressure (bar)	$3.3^{+26.7}_{+1.81} - 2.1 \times 10^3$ (outer) – $1.39 - 0.76 \times 10^6$ (inner)	Decker & Decker, 1992 Fowler, 1990 Lodders & Fegley, 1998 Davies, 1999
Depth (km)	5-2890 (average 33 under continents; 7 under oceans)	Decker & Decker, 1992 Scheidegger, 1976 Dziewonski & Anderson, 1981
Density (kg m^{-3})	4.5×10^3	Lodders & Fegley, 1998
Mean pressure gradient (Pa km^{-1})	4.41×10^4	Lodders & Fegley, 1998 Dziewonski & Anderson, 1981
Geothermal gradient (K km^{-1})	0.3-1 our model 0.7	Mason, 1958 Schiano <i>et al.</i> (2006)

Continental crust

<i>Temperature (K)</i>	184-331(surface) ~800(average base temp; magma)	Lodders & Fegley, 1998 Huppert & Sparks, 1988
<i>Pressure (bar)</i>	1 (surface) - $1.3^{+0.9}_{-1.03} \times 10^4$ (base)	Lodders & Fegley, 1998
<i>Thickness (km)</i>	35 (mean) 10-80 range	Dziewonski & Anderson, 1981 Scheidegger, 1976 Burtman & Molnar (1993)
<i>Density (kgm⁻³)</i>	2.8×10^3	Lodders & Fegley, 1998
<i>Mean pressure gradient (Pa km⁻¹)</i>	2.74×10^4	Lodders & Fegley, 1998 Dziewonski & Anderson, 1981
<i>Geothermal gradient (K km⁻¹)</i>	25 (mean)	Scheidegger, 1982

Oceanic crust

<i>Temperature (K)</i>	271 – 737 (ocean floor)	National Oceanic and Atmospheric Administration (2007) website Koschinsky <i>et al.</i> (2008)
<i>Pressure (bar)</i>	4×10^2 (base ocean)- $1.9^{+4.38}_{-0.33} \times 10^3$ (Moho)	Lodders & Fegley, 1998
<i>Thickness (km)</i>	5 (mean oceanic) 4 – 20 (range) 4 (mean depth under ocean)	Dziewonski & Anderson, 1981 Muller <i>et al.</i> (1997) Mooney <i>et al.</i> (1998)
<i>Mean pressure gradient (Pa km⁻¹)</i>	2.94×10^4	Lodders & Fegley, 1998 Dziewonski & Anderson, 1981
<i>Density (kg m⁻³)</i>	3×10^3	Lodders & Fegley, 1998
<i>Geothermal gradient (K km⁻¹)</i>	40	Scheidegger, 1982

Atmosphere

<i>Mean lapse rate temperature (K km⁻¹)*</i>	6.5 troposphere -2.0 stratosphere 2.6 mesosphere -5.8 thermosphere	Hewitt & Jackson, 2003 West, 1996. Choi <i>et al</i> 1998
<i>Lapse rate pressure (Pa km⁻¹)**:</i> below 86 km	$-0.0012 \left(1 - \frac{z}{44307.69} \right)^{4.26}$	National Oceanic and Atmospheric Administration (2007)

website
Pearson & Ruge
(1976)

*Temperature lapse rate Γ_T is the rate of decrease of temperature with height: $\Gamma_T(z) = -dT/dz$

**Pressure lapse rate Γ_P is the rate of decrease of pressure with height: $\Gamma_P(z) = dP/dz$ using the equation:

$z = [1 - (P/10.13)^{0.19}] \times 44307.69$ where z = altitude (km) and P = static pressure (Pa) (Pearson & Ruge, 1976)

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 be cool, however, 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 Earth's heat flow, which is not explicitly represented in our model. 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⁻¹K⁻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 ~ 200 km in the asthenosphere where convective heat transfer dominates (Andersen, 1979; Chapman, 1986). In our model, the oceanic and continental geotherms converge at ~ 10 km into the continental crust. A typical geothermal gradient in the oceanic crust is ~ 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 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 ~ 80 K km $^{-1}$) and so is consistent with the range of true geothermal gradients on Earth.

Core

Earth's core extends from a depth of 2890 km to 6378 km. At the center, the pressure is modeled as 3.6×10^6 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 $2.8 - 3.8 \times 10^6$ bar (Fowler, 1990; Lodders & Fegley, 1998). Similarly, we have chosen a representative pressure value for the core-mantle boundary (CMB) of 1.4×10^6 bar (Davies, 1999) within the range of $0.6 - 3.2 \times 10^6$ 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 & Wysession, 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 & Wysession, 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

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 3.3×10^3 bar and 800 K, which is 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 modeled 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).

Appendix B Explanatory Details for Tables 3 and 4.

Life has been found throughout 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 (e.g., *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 unfavorable conditions. This means that spores collected from the atmosphere can be dormant and yet viable, and so they 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 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 ~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 $\sim 10^{-5}$ bar, -70 °C respectively) where spores (eg., *Circinella muscae*) were isolated (Imshenetsky *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 in our life regime in Figure 4.

A serious limitation on atmospheric life's capacity to remain active may be the transient nature of low pressure liquid water environments. The presence of life in clouds is strongly linked to the availability of liquid water. Studies of low altitude atmospheric life (samples from <4km above sea level, Amato *et al.*, 2005,2007; Sattler, *et al.* 2001; Bauer, *et al.* 2002) have found that the majority of microbes in the clouds are dormant, but viable, and remain alive by utilizing cloud water. This suggests that surface life can persist at altitudes up to the triple point of ocean salinity water at ~25 km altitude (Fig. 3); however,

this life will be largely, or entirely, dormant. Samples isolated at higher altitudes (e.g. ~41 km, Wainwright *et al.*, 2002) have a much lower percentage of viable micro-organisms, which may be due to the additional stress of almost no cloud water. Cloud water could persist to higher altitudes (lower atmospheric pressures) if it is briny; however, models of liquid water clouds indicate that water content reaches a minimum at < 20 km altitude (Figure 7 of http://meteora.ucsd.edu/~iacob/scm_recent/arm3/poster.html; Iacobellis *et al.*, 2003).

References

- Abyzov, S., Mitskevich, I., Poglavova, M. (1998) Microflora of the deep glacier horizons of central Antarctica. *Microbiology* 67, 451-458.
- Amato, P., Menager, M., Sancelme, M., Laj, P., Mailhot, G., Delort, A. (2005) Microbial population in cloud water at the Puy de Dome: implications for the chemistry of clouds. *Atmos. Environ.* 39, 4143-4153.
- Amato, P., Parazols, M., Sancelme, M., Mailhot, G., Laj, P., Delort, A. (2007) An important oceanic source of micro-organisms for cloud water at the Puy de Dome (France). *Atmos. Environ.* 41, 8253-8263.
- Amend, J., Meyer-Dombard, D., Sheth, S., Zolotova, N., Amend, A. (2003) *Palaeococcus helgesonii* sp. nov., a facultatively anaerobic, hyperthermophilic archaeon from a geothermal well on Vulcano Island, Italy. *Arch. Microb.* 179, 394-401.
- Andersen, D., Pollard, W., McKay, C., Heldmann, J. (2002) Cold springs in permafrost on Earth and Mars. *J. Geophys. Res. (Planets)* 107, 4.1-4.7.
- Andersen, D. (1979) The deep structure of continents. *J. Geophys. Res.* 84, 7555-7560.
- Artemieva, I. (2006) Global 1°x1° thermal model TC1 for the continental lithosphere: implications for lithosphere secular evolution. *Tectonophysics* 416, 245-277.
- Barlow, N. (2008) *Mars: An introduction to its interior, surface and atmosphere*. Cambridge University Press, Cambridge, UK.
- Baross, J., Benner, S., Cody, G., Copley, S., Pace, N., Scott, J., Shapiro, R., Sogin, M., Stein, J., Summons, R., Szostak, J., (2007) *The limits of organic life in planetary systems*. National Research Council, National Academies Press, Washington, DC.
- Bauer, H., Kasper-Giebl, A., Loflund, M., Giebl, H., Hitznerberger, R., Zibuschka, F., Pauxbaum, H. (2002) The contribution of bacterial and fungal spores to the organic carbon content of cloud water, precipitation and aerosols. *Atmos. Res.* 64, 109-119.
- Blackwell, D. (1971) The thermal structure of the continental crust. In *The Structure and Physical Properties of the Earth's Crust*, edited by J.G. Heacock, Geophysical Monograph 14, Washington, DC, 169-184.
- Burtman, V., Molnar, P. (1993) *Geological and geophysical evidence for deep subduction of continental crust beneath the Pamir*. Geological Society of America, Boulder, Colorado.
- Čermák, V., Šafanda, J., Guterch, A. (1989) Deep temperature distribution along three profiles crossing the Teisseyre-Tornquist tectonic zone in Poland. *Tectonophysics* 164, 151-163.
- Chapman, D. (1986) Thermal gradients in the continental crust. *J. Geol. Soc. London (Special Publications)* 24, 63-70.
- Chapman, D., Pollack, H. (1975) Global heat flow – a new look. *Earth Planet. Sci. Lett.* 28, 23-32.

- Choi, G., Monson, I., Wickwar, V., Rees, D. (1998) Seasonal variations of temperature near the mesopause from Fabry-Perot interferometer observations of OH Meinel emissions. *Adv. Space Res.* 21, 843 – 846.
- Clark, B., Van Hart, D. (1981) The salts of Mars. *Icarus* 45, 370-378.
- Clauser, R., Huenges, E. (1995) Thermal conductivity of rocks and minerals. In *Rock Physics and Phase Relations – A Handbook of Physical Constants*, edited by T. Ahrens, American Geophysical Union, Washington, DC, 105-126.
- Davies, G. (1999) *Dynamic Earth: plates, plumes, and mantle convection*. Cambridge University Press, Cambridge, UK.
- Davis, N. (2001) *Permafrost, A Guide to Frozen Ground in Transition*. University of Alaska Press, Fairbanks.
- Decker, B., Decker, R. (1992) *Mountains of fire: the nature of volcanoes*. Cambridge University Press, Cambridge, UK.
- Doornbos, D. (1983) Present seismic evidence for a boundary layer at the base of the mantle. *J. Geophys. Res.* 88, 3498-3505.
- Dziewonski, A., Anderson, D. (1981) Preliminary reference Earth model. *Phys. Earth Planet. Inter.* 25, 297-356.
- Ellis, A., Mahon, W. (1977) *Geochemistry and geothermal systems*. Academic Press, New York.
- Ellsworth, E., Hickman, S., Zoback, M., Davis, E., Gee, L., Huggins, R., Krug, R., Lippus, C., Malin, P., Neuhauser, D., Paulsson, B., Shalev, E., Vajapeyam, B., Weiland, C., Zumberge, M. (2005) Observing the San Andreas Fault at depth. *American Geophysical Union, Fall Meeting*, abstract #T24B-04.
- Ernst, W. (1990) *The dynamic planet*. Columbia University Press, New York.
- Fagents, S., Greeley, R. (2001) Factors influencing lava-substrate heat transfer and implications for thermochemical erosion. *Bull. Volcanol.* 62, 519-532.
- Fowler, C. (1990) *The solid earth: an introduction to geophysics (1st Ed)*. Cambridge University Press, Cambridge, UK.
- Gangwar, P., Alam, S., Bansod, S., Singh, L. (2009) *Canad. J. Microbiol.*, 55, 564-577.
- Garzón, L. (2004) Microbial life and temperature: a semi empirical approach. *Orig. Life. Evol. Biosph.* 34, 421-438.
- Grant, W. (2004) Life at low water activity. *Phil. Trans. R. Soc. Lond. B* 359, 1249-1267.
- Griffin, D. (2008) Non-spore forming eubacteria isolated at an altitude of 20,000m in Earth's atmosphere: extended incubation periods needed for culture based assays. *Aerobiologia* 24, 19-25.
- Griffith, C., Hall, J., Geballe, T. (2000) Detection of daily clouds on Titan. *Science* 290, 509-513.
- Guidry, S., Chafetz, H. (2003) Anatomy of siliceous hot springs: examples from Yellowstone National Park, Wyoming, USA. *Sediment. Geol.* 157, 71-106.
- Harris, A., Flynn, L., Keszthelyi, L., Mougini-Mark, P., Rowland, S., Resing, J. (1998) Calculation of lava effusion rates from Landsat TM data. *Bull. Volcanol.* 60, 52-71.
- Helz, R., Thornber, C. (1987) Geothermometry of Kilauea Iki lava lake, Hawaii. *Bull. Volcanol.* 49, 651-668.
- Hewitt, C., Jackson, A. (2003) *Handbook of atmospheric science – principles and applications*. Wiley-Blackwell Publishers, New York.

- Hoehler, T. (2004) Biological energy requirements as quantitative boundary conditions for life in the subsurface. *Geobiology* 2, 205 – 215.
- Hoehler, T., Amend, J., Shock, E., (2007) A ‘follow the energy’ approach for astrobiology. *Astrobiology* 7, 819-823.
- Holbig, E., Grove, T. (2008) Mantle melting beneath the Tibetan Plateau: experimental constraints on ultrapotassic magmatism. *J. Geophys. Res.* 113, B04210.
- Holden, J. (2008) Some like it Hot: understanding the limits of life using hyperthermophilic microbes, 37th COSPAR Scientific Assembly Symposium F, Session 33, Paper # 33-0015-08, 1259.
- Horikoshi, K. (1998) Barophiles: deep-sea microorganisms adapted to an extreme environment. *Curr. Opin. Microbiol.* 1, 291-295.
- Horsfeld, B., Schenk, H., Zink, K., Ondrak, R., Dieckmann, V., Kallmeyer, J., Mangelsdorf, K., di Primio, R., Wilkes, H., Parkes, R., Fry, J., Cragg, B. (2006) Living microbial ecosystems within the active zone of catagenesis: implications for feeding the deep biosphere. *Earth Planet. Sci. Lett.* 246, 55-69.
- Hubbard, G. S., Naderi, F.M., Garvin, J.B. (2002) Following the water, the new program for Mars exploration. *Acta Astron.* 51, 1-9, 337-350.
- Huppert, H., Sparks, R. (1988) The generation of granitic magmas by intrusion of basalt into continental crust. *J. Petrol.* 29, 599-624.
- Hyndman, R., Currie, C., Mazzotti, S. (2005) Subduction zone backarcs, mobile belts, and orogenic heat. *Geological Soc. Amer. Today* 15, 4-10.
- Iacobellis, S., Sommerville, R., McFarquhar, G., Mitchell, D. (2003) Sensitivity of cloud-radiation interactions to cloud microphysics. Fourteenth *Symposium on Global Changes and Climate Variations*, Long Beach, CA, February 9-13.
- Imshenetsky, A., Lysenko, S., Kazakov, G. (1978) Upper boundary of the biosphere. *Appl. Environ. Microbiol.* 35, 1-5.
- Jakosky, B., Amend, J., Berelson, W., Blake, R., Brantley, S., Carr, M., Fredrickson, J., Keefe, A., Keller, M., McSween, H., Nealson, K., Sherwood-Lollar, B., Steele, A., Summons, R., Wadhwa, M. (2007) *An astrobiology strategy for the exploration of Mars*. National Research Council, National Academies Press, Washington, DC.
- Jeanloz, R. (1990) The nature of the Earth’s core. *Annu. Rev. Earth Planet. Sci.* 18, 357-386.
- Jiménez-Munt, I., Fernández, M., Vergés, J., Platt, J. (2008) Lithosphere structure underneath the Tibetan plateau inferred from elevation, gravity and geoid anomalies. *Earth Planet. Sci. Lett.* 267, 276-289.
- Jones, E., Lineweaver, C. (2008). Identifying the potential biosphere of Mars. In *Australian Space Science Conference Series: 7th Conference Proceedings NSSA*, 7, National Space Society of Australia, 60-72.
- Jonsson, V., Matthiasson, M., (1974) Lava cooling on Heimaey – methods and procedures. In *Proceedings of the Icelandic Association of Chartered Engineers*, 59, Icelandic Association of Chartered Engineers, 70-81.
- Junge, K., Eicken, H., Deming, J. (2004) Bacterial activity at -2 to -20°C in Arctic wintertime sea ice. *Appl. Environ. Microbiol.* 70, 550-557.
- Karato, S. (2003) *The dynamic structure of the deep Earth: an interdisciplinary approach*. Princeton University Press, Princeton, New Jersey.
- Kashefi, K., Lovley, D. (2003) Extending the upper temperature limit for life. *Science* 301, 934.

- Kelley, D.S. et al (2007) Towards Determining the Upper Temperature Limit to Life, *Eos Trans. AGU Fall Meeting Suppl.* 88, Abstract V23D-02, 52.
- Koschinsky, A., Garbe-Schonberg, D., Sander, S., Schmidt, K., Gennerich, H., Strauss, H. (2008) Hydrothermal venting at pressure-temperature conditions above the critical point of seawater, 5°S on the mid-Atlantic ridge. *Geology* 36, 615-618.
- Langdahl, B., Ingvorsen, K. (1997) Temperature characteristics of bacterial iron solubilisation and ^{14}C assimilation in naturally exposed sulfide ore material at Citronen Fjord, North Greenland (83°N). *FEMS Microbiol. Ecol.* 23, 275-283.
- Lide, D., Frederikse, H. (1996) *CRC Handbook of chemistry and physics (77th Ed.)*. CRC Press, Boca Raton, Florida.
- Lide, D., Haynes, W. (2009) *CRC Handbook of chemistry and physics (90th Ed.)*. CRC Press, Boca Raton, Florida.
- Lodders, K., Fegley, B. (1998) *The planetary scientist's companion*. Oxford University Press, Oxford, UK.
- Margosch, D., Ehrmann, M., Buckow, R., Heinz, V., Vogel, R., Ganzle, N. (2006) High-pressure-mediated survival of *Clostridium botulinum* and *Bacillus amyloliquefaciens* endospores at high temperature. *App. Environ. Microb.* 72, 3476-3481.
- Mariana Trench (2003) available at http://www.marianatrench.com/mariana_trench-biology_001.htm
- Mason, B. (1958) *Principles of geochemistry*. John Wiley and Sons, New York.
- Melosh, H., Ekholm, A., Showman, A., Lorenz, R. (2004) The temperature of Europa's subsurface water ocean. *Icarus* 168, 498-502.
- Möhlmann, D. (2008) The influence of van der Waals forces on the state of water in the shallow subsurface of Mars. *Icarus* 195, 131-139.
- Mohorovičić, A. (1909) Earthquake of 8 October 1909. *Geofizika* 9, 3-55.
- Mooney, W., Laske, G., Masters, G. (1998) A global crustal model at 5° x 5°. *J. Geophys. Res.* 103, 727-747.
- Muller, M., Robinson, C., Minshull, T., White, R., Bickle, M. (1997) Thin crust beneath ocean drilling program borehole 735B at the Southwest Indian Ridge? *Earth Planet. Sci. Lett.* 148, 93-107.
- Nakagawa, T., Tackley, P. (2004) Effects of thermo-chemical mantle convection on the thermal evolution of the Earth's core. *Earth Planet. Sci. Lett.* 220, 107-119.
- National Oceanic and Atmospheric Administration (NOAA), Satellite and Information Service (2007) available at <http://www.ncdc.noaa.gov/oa/>
- Oppenheimer, C., Francis, P. (1998) Implications of longeval lava lakes for geomorphological and plutonic processes at Erta 'Ale volcano, Afar. *J. Volcan. Geother. Res.* 90, 101-111.
- Pavlenkova, N., Zverev, S. (1981) Seismic model of Iceland's crust. *Int. J. Earth Sci.* 70, 271-281.
- Pearson, J., Rugge, H. (1976) US Standard Atmosphere. *National Ocean and Atmospheric Administration*, US Government printing office, Washington, DC.
- Petculescu, A., Lueptow, R. (2007) Atmospheric acoustics of Titan, Mars, Venus and Earth. *Icarus* 186, 413-419.
- Pollack, H., Chapman, D. (1977) On the regional variation of heat flow, geotherms, and lithospheric thickness. *Tectonophysics* 38, 279-296.
- Price, P. (2000) A habitat for psychrophiles in deep Antarctic ice. *PNAS* 97, 1247-1251.

- Price, P., Sowers, T. (2004) Temperature dependence of metabolic rates for microbial growth, maintenance, and survival. *PNAS* 101, 4631-4636.
- Price, P., Nagornov, O., Bay, R., Chirkin, D., He, Y., Miocinovic, P., Richards, A., Woschnagg, K., Koci, B., Zagorodnov, V. (2002) Temperature profile for glacial life at the south pole: implications for life in a nearby subglacial lake. *PNAS* 99, 7844-7847.
- Priestley, K., Jackson, J., McKenzie, D., (2008) Lithospheric structure and deep earthquakes beneath India, the Himalaya and southern Tibet. *Geophys. J. Int.* 172, 345-362.
- Prol-Ledesma, R. (2003) Similarities in the chemistry of shallow submarine hydrothermal vents. *Geothermics* 32, 639-644.
- Reynolds, R., Squyres, S., Colburn, D., McKay, C. (1983) On the habitability of Europa. *Icarus* 56, 246-254.
- Rothschild, L., Mancinelli, R. (2001) Life in extreme environments. *Nature* 409, 1092-1101.
- Sattler, B., Pauxbaum, H., Psenner, R. (2001) Bacterial growth in supercooled cloud droplets. *Geophys. Res. Lett.* 28, 243-246.
- Saxena, S., Shen, G., Lazor, P. (1994) Temperatures in Earth's core based on melting and phase transformation experiments on iron. *Science* 264, 405-407.
- Scheidegger, A. (1976) *Foundations of geophysics*. Elsevier Scientific Pub. Co., Amsterdam, New York.
- Schiano, P., Provost, A., Clocchiatti, R., Faure, F. (2006) Transcrystalline melt migration and Earth's mantle. *Science* 314, 970-974.
- Schrenk, M., Kelley, D., Delaney, J., Baross, J. (2003) Incidence and Diversity of Microorganisms within the Walls of an Active Deep-Sea Sulfide Chimney. *App. Environ. Microbiol.* 69, 3580-3592.
- Slater, J., Francheteau, J. (1970) The implications of terrestrial heat flow observations on current tectonic and geochemical models of the crust and upper mantle of the earth. *Geophys. J. R. Astr. Soc.* 20, 509-542.
- Sharma, A., Scott, J., Cody, G., Fogel, M., Hazen, R., Hemley, R., Huntress, W. (2002) Microbial activity at gigapascal pressures. *Science* 295, 1515-1516.
- Shock, E.L., Holland, M.E., (2007) Quantitative habitability. *Astrobiology* 7, 839-851.
- Silberberg, M., Duran, R. (2002) *The molecular nature of matter and change*. McGraw-Hill, University of Virginia, Charlottesville, Virginia.
- Sleep, N., Zoback, M. (2007) Did earthquakes keep the early crust habitable? *Astrobiology* 7, 1023-1032.
- Smith, P. (1973) *Topics in geophysics*. MIT Press, Cambridge, Massachusetts.
- Sokolova, L., Duchkov, A., Čermák, V. (1978) Crustal thermal models for South Siberia. *Stud. Geophys. Geod.* 22, 200-207.
- Stacey, F., Loper, D. (1984) Thermal histories of the core and mantle. *Phys. Earth Planet. Inter.* 36, 99-115.
- Stein, D., Spera, F. (2002) Shear viscosity of rhyolite-vapor emulsions at magmatic temperatures by concentric cylinder rheometry. *J. Volcan. Geotherm. Res.* 113, 243-258.
- Stein, S., Wysession, M. (2003) *An introduction to seismology, earthquakes, and earth structure*. Wiley-Blackwell Publishers, Malden, Massachusetts.
- Stetter, K. (2006) History of discovery of the first hyperthermophiles. *Extremophiles* 10, 357-362.
- Stoffers, P., Worthington, T., Schwarz-Schampera, U., Hannington, M., Massoth, G., Hekinian, R., Schmidt, M., Lundsten, L., Evans, L., Vaiomo'unga, R., Kerby, T. (2006) Submarine

- volcanoes and high-temperature hydrothermal venting on the Tonga arc, southwest Pacific. *Geology* 34, 453-456.
- Szewzyk, U., Szewzyk, R. (1994) Thermophilic, anaerobic bacteria isolated from a deep borehole in granite in Sweden. *PNAS* 91, 1810-1813.
- Takai, K., Nakamura, K., Toki, T., Tsunogai, U., Miyazaki, M., Miyazaki, J., Hirayama, H., Nakagawa, S., Nunoura, T., Horikoshi, K. (2008) Cell proliferation at 122°C and isotopically heavy CH₄ production by a hyperthermophilic methanogen under high-pressure cultivation. *PNAS* 105, 10949-10954.
- Takami, H., Inoue, A., Fuji, F., Horikoshi, K. (1997) Microbial flora in the deepest sea mud of the Mariana trench. *FEMS Microbiol. Lett.* 152, 279-285.
- Team Everest (2003) available at <http://www.teameverest03.org>
- Todo, Y., Kitazoto, H., Hashimoto, J., Gooday, A. (2005) Simple foraminifera flourish at the ocean's deepest point. *Science* 307, 689.
- Wainwright, M., Narlikar, J., Rajaratnam, P. (2002) Microorganisms cultured from stratospheric air samples obtained at 41 km. *FEMS Microbiol. Lett.* 10778, 1-5.
- Wainwright, M., Wickramasinghe, N., Narlikar, J., Rajaratnam, P., Perkins, J. (2004) Confirmation of the presence of viable but non-cultureable bacteria in the stratosphere. *Int. J. Astrobiol.* 3, 13-15.
- Wainwright, M., Alharbi, S., Wickramasinghe, N. (2006) How do microorganisms reach the stratosphere? *Int. J. Astrobiol.* 5, 13-15.
- Weir, T., Erzinger, J. (2008) Origin and spatial distribution of gas at seismogenic depths of the San Andreas Fault from drill-mud gas analysis. *App. Geochem.* 23, 1675-1690.
- West, J., Lahiri, S., Maret, K., Peters Jr., R., Pizzo, C. (1983) Barometric pressures on Mt Everest: new data and physiological significance. *J. Appl. Physiol.* 54, 1188-1194.
- West, J. (1996) Prediction of barometric pressures at high altitudes with the use of model atmospheres. *J. Appl. Physiol.* 81, 1850-1854.
- Williams, Q., Garnero, E. (1996) Seismic evidence for partial melt at the base of the Earth's mantle. *Science* 273, 1528.
- Zerr, A., Diegeler, R., Boehler, R. (1998) Solidus of the Earth's deep mantle. *Science* 280, 243.