Lecture 7: Requirements for Life

Aims of Lecture

(1) To discuss the basic requirements for life that we would expect to be common throughout the Universe;

(2) To discuss how life survives on Earth in extreme environments, and what this implies for life elsewhere.

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Fig. 1. Abundant life at the Galapagos Rift hydrothermal field (NOAA/Public Domain).

1. Introduction

As far as we know, there are at least three basic requirements which must be satisfied wherever life exists (Fig. 1 shows an example in an astrobiologically relevant setting on Earth):

- A source of raw materials (either organic molecules already present in the environment, or simpler substances from which these can be manufactured);
- A source of energy;
- A liquid medium (probably water) within which the chemical reactions on which life depends (and which actually constitute life by Joyce's definition as given in Lecture 5) can take place.

2. A source of organics

The justification for believing that carbon-based (i.e. organic) molecules are essential for life was given in Lecture 4. Given this, living systems have two choices: they can either obtain organic molecules from their environment, or they can manufacture them from simpler substances.

2.1 Heterotrophs

Organisms which obtain organic materials from their environment (i.e. by eating them) are called heterotrophs, derived from Greek words meaning ‘other’ and “to feed”. All animals are heterotrophs, and so are many micro-organisms.

2.2 Autotrophs

Organisms which manufacture their own organic molecules are known as autotrophs. There is then a further distinction depending on whether the energy is derived from sunlight (photoautotrophs) or chemical sources (chemoautotrophs).

(a) Photoautotrophs

Photoautotrophs manufacture (‘synthesise’) organic material through photosynthesis, which can be represented chemically as:

$$\mathbf{2H_2X + CO_2 + light \rightarrow \text{“}CH_2O\text{”} + H_2O + 2X}$$

Here, X represents an unspecified atom; it is oxygen (O) for the familiar oxygenic photosynthesis of cyanobacteria, algae and green plants, but can be sulphur for anoxygenic photosynthesis which is employed by some bacteria; “CH_2O” represents synthesised organic compounds (e.g. sugars). Note that the arrow here hides a lot of biochemical complexity.

(b) Chemoautotrophs

An example of chemosynthesis is:

$$H_2S + CO_2 + O_2 + H_2O \rightarrow \text{“}CH_2O\text{”} + H_2SO_4$$

Again, it is important to note that these simple chemical reactions merely summarise the biological synthesis (‘biosynthesis’) of organic molecules – in actual living cells synthesis occurs through complicated metabolic pathways mediated by appropriate enzymes.

3. Energy

Photoautotrophs and chemoautotrophs derive their energy from sunlight and chemical sources, respectively. In principle, heterotrophs can also gain energy from sunlight (as photoheterotrophs), but these are represented by only a handful of microbial species. Most heterotrophs gain energy from chemical sources (as chemoheterotrophs). The full range of possibilities, and the appropriate nomenclature, is given in Table 1.

Table 1. Summary of metabolic classifications.

Metabolic classification	Carbon source	Energy source	Examples
Photo-autotrophs	CO_2	Sunlight	Photosynthetic bacteria; plants
Chemo-autotrophs	CO_2, CH_4	Inorganic e^- donor	Some prokaryotes (esp. extremophiles)
Chemo-heterotrophs	Organic compounds	Inorganic e^- donor (litho-chemotrophs)	Some prokaryotes
		Organic compounds (organo-chemotrophs)	Animals
Photo-heterotrophs	Organic compounds	Sunlight	Some prokaryotes

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Note that some micro-organisms, dubbed ‘mixotrophs’, can switch between these metabolic strategies to suit their environment. We now discuss in more detail some of the mechanisms used by chemotrophs to extract energy from their surroundings:

3.1 Fermentation

Fermentation is a way of extracting energy by breaking down glucose molecules, obtained from the environment, into smaller molecules. It does not require oxygen, and so could have worked on the early Earth. However, it is quite inefficient as only a relatively small fraction of the energy contained in the initial glucose molecules is extracted. The first step of fermentation, known as glycolysis, may be represented as:

$$\mathbf{C_6H_{12}O_6 \rightarrow 2CH_3COCOO^- + 2H^+ + 2H_2 + Energy}$$

The product $2CH_3COCOO^-$ is called pyruvate, and the reaction produces sufficient energy to convert two molecules of ADP into ATP. Following glycolysis, the pyruvate a range of organic substances, such as ethanol and lactic acid.

3.2 Aerobic respiration

Aerobic respiration extracts energy from glucose by combining it with oxygen. It is much more efficient than fermentation, making up to 36 ATP molecules per glucose molecule (although the number is closer to 30 in practice), but it requires oxygen to be available in the environment. It may be represented chemically as:

$$\mathbf{C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O + Energy}$$

Remember that aerobic respiration was first discovered/invented by bacteria, and is still employed by many. We have seen (Lecture 6) that the eukaryotic cells of animals, which depend on aerobic respiration, acquired it through the symbiotic incorporation of aerobic bacteria as mitochondria.

3.3 Anaerobic respiration

Anaerobic respiration is also possible, and is employed by a number of bacterial species. For example, sulphate reducing bacteria take in (‘breath’) sulphate ions to break down organic molecules and release energy:

$$C_6H_{12}O_6 + 3SO_4^{2-} \rightarrow 3S^{2-} + 6CO_2 + 6H_2O + \text{Energy}$$

Because sulphate is much less efficient as an oxidising agent than molecular oxygen, and the reaction requires an investment of energy to initiate, it releases much less energy overall than aerobic respiration (with a net gain of ~1 ATP molecule).

3.4 Redox reactions

Chemotrophs can extract energy from a wide range of reduction-oxidation (redox) reactions. Chemically, oxidation is defined as the removal of electrons from a substance, and reduction as the addition of electrons. Redox reactions release energy when one molecule (the electron donor) gives up an electron to another (the electron acceptor), which thereby becomes reduced.

A wide variety of simple inorganic molecules, widely available in the environment, can act as electron donors; examples include H_2, H_2S, CH_4, and NH_3.

Common electron acceptors include O_2, CO_2, and SO_4.

Atoms or molecules like CO, S and Fe can act as either electron acceptors or electron donors depending on what they react with.

The key point is that this wide variety of possible redox reactions results in a correspondingly large variety of possible microbial metabolisms.

For example, consider some of the possibilities involving sulphur compounds (in each case the electron donor is indicated in red):

Sulphide oxidation: $\mathbf{2H_2S + O_2 \rightarrow 2S + 2H_2O}$

Sulphur oxidation: $\mathbf{2S + 3O_2 + 2H_2O \rightarrow 2H_2SO_4}$

Sulphate reduction: $\mathbf{4H_2 + H_2SO_4 \rightarrow H_2S + 4H_2O}$

Below we give some other examples of redox reactions utilised by various types of microbes:

(i) Methanogenic archaea: $\mathbf{CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O}$

(ii) Acetogenic bacteria: $\mathbf{2CO_2 + 4H_2 \rightarrow CH_3COOH + 2H_2O}$

(iii) Iron reducing bacteria: $\mathbf{2Fe^{3+} + H_2 \rightarrow 2Fe^{2+} + 2H^+}$

(iv) Iron oxidising bacteria: $\mathbf{2Fe^{2+} + 0.5O_2 + 2H^+ \rightarrow 2Fe^{3+} + H_2O}$

3.5 Geological sources of hydrogen

Many of these redox reactions use H_2 as an electron donor, and it is important to determine whether naturally occurring sources of H_2 are likely to exist in suitable planetary environments. Fortunately, there are at least two processes which may produce the required hydrogen in sufficient quantities for chemosynthetic organisms to utilise: the serpentinization of mafic silicates and the radiolysis of water.

(a) Serpentinization Reactions

Water can react with Fe-bearing minerals in silicate rocks to produce the mineral serpentine and release hydrogen. A common example is the reaction between water and olivine:

$$\mathbf{3MgFeSiO_4\ [olivine] + 3H_2O\ [water] \longrightarrow}$$

$$\mathbf{Mg_3Si_2O_5(OH)_4\ [serpentine] + SiO_2\ [quartz] + Fe_3O_4\ [magnetite] + H_2}$$

Given that basaltic volcanism (which produces lavas rich in Fe-bearing minerals like olivine and pyroxene) is ubiquitous on terrestrial planets, serpentinization reactions like this are inevitable on any such planets where water is also present.

Serpentinization reactions are thought to provide hydrogen for chemosynthetic microorganisms found deep in Earths crust (see Section 6.4). They are likely to have occurred on a warmer and wetter early Mars (and may still do so within the crust where geothermal heat melts an overlying cryosphere; Lecture 8), and may occur at the boundaries between liquid water and rocky silicate mantles on icy outer planet moons such as Europa and Enceladus. Indeed, wet, rocky planets providing the necessary conditions are likely to be extremely common in the Galaxy as a whole.

(b) Radiolysis of water

Naturally occurring radioactive atoms found in planetary crusts (e.g. U, Th and ^{40}K) decay by emitting high-energy particles which are able to dissociate water molecules into hydrogen and oxygen:

$$H_2O \xrightarrow{\text{Radiation}} OH + H$$

The dissociation of water by radiolysis has been suggested to be a source of hydrogen used by some terrestrial chemosynthetic organisms and, like serpentinization reactions, will occur on any wet terrestrial planet with a rocky crust. Note also that reactions between OH (and OH-derived H_2O_2) with elements in the rocks may also produce electron acceptors (e.g. SO_4).

3.6 Symbiosis

Some organisms obtain energy and/or organic raw materials
through symbiotic relationships with primary producers:

- Eukaryotic cells (chloroplasts; mitochondria);
- Many corals and related marine animals have incorporated symbiotic photosynthetic algae into their tissues (e.g. Fig. 2);
- Many of the large animals found at hydrothermal vents (e.g. the giant tube worms, *Riftia pachyptila*; Fig. 1) incorporate chemosynthetic (typically sulphide oxidising) bacteria.

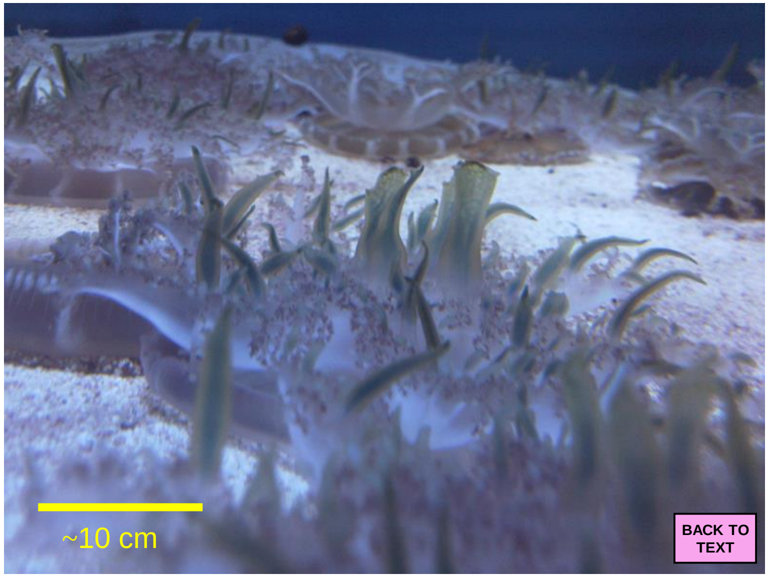

Fig. 2. The 'upside-down jellyfish' (*Cassiopeia xamachana*). The green tentacles contain photo-synthetic algae which provide a source of energy and oxygen, the latter enabling the animal to live in oxygen-poor waters. (Moody Gardens Aquarium, Galveston, Texas; photo: I.A. Crawford).

3.7 Astrobiological implications

The huge variety of possible ways in which life can obtain energy from its environment translates into an equally wide variety of potential habitats. This is the main point to bear in mind from an astrobiological perspective as it shows that energy sources for life are likely to be available in a wide range of different planetary environments.

4. The importance of water

Life requires a liquid medium within which organic molecules are mobile, and within which they can react. On Earth this role is performed by liquid water. There are several reasons for thinking that water is uniquely suitable as a medium for life:

(i) Of all the volatile substances likely to be liquid in planetary environments water is by far the most common.

(ii) Other potential substances are liquid at much lower temperatures, and over a narrower temperature range (Table 2). The lower temperatures are less conducive to biochemical reactions, and the narrow temperature ranges make the preservation of a liquid state much more sensitive to climatic variations.

Table 2. Properties of some possible planetary surface liquids (at a pressure of 1 bar)

Substance	Freezing point	Boiling point	Temp. range for liquid state
Water (H_2O)	0°C	100°C	100°C
Ammonia (NH_3)	−78°C	−33°C	45°C
Methane (CH_4)	−182°C	−164°C	18°C
Ethane (C_2H_6)	−183°C	−89°C	94°C

(iii) As a related point: in terms of planetary evolution the fact that ice floats, whereas the solid phases of most other liquids sink, is important as it greatly increases the chance of a liquid reservoir surviving a lowering of planetary temperatures. That is, it provides a *buffer* against climatic fluctuations, and thereby effectively increases the width of the habitable zone.

(iv) Water is not merely a passive solvent, but is involved directly in many biochemical reactions. For example ATP hydrolysis (which releases energy from ATP), and the formation and breaking of peptide bonds between amino acids. Moreover, water is a polar molecule (Fig. 3) and this is responsible for the hydrophobic – hydrophilic response involved in phospholipid membranes and in protein folding. However, we don't know to what extent these biochemical properties are essential to life in general, or merely to Earth life that evolved in a watery environment. Note that, of the molecules listed in Table 2, ammonia is also a polar molecule, but the others are not.

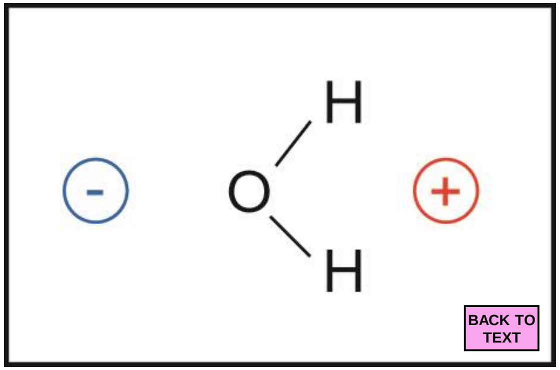

Fig. 3. Electrical polarity of a water molecule. Although electrically neutral overall, the distribution of electrons causes the oxygen-bearing end to be negatively charged, and the hydrogen-bearing part to be positively charged.

5. Extremophiles

We now know that life can exist over a much broader range of physical conditions than was realised only a few decades ago, provided that the basic requirements (carbon, energy, and liquid water) are available. Organisms (almost all prokaryotes) which survive, or even thrive, in environments which we might consider extreme are called 'extremophiles'. We can distinguish between organisms which can merely tolerate extreme conditions, and true extremophiles which are actually *adapted* to them. We can recognized organisms adapted to high temperature (thermophiles), low temperature (psychrophiles), high salinity (halophiles), low pH (acidophiles), high pH (alkaliphiles), and high pressure (piezophiles).

An recent review of of the literature on extremophiles from an astrobiology perspective has been provided by Nancy Merino et al., "Living at the Extremes: Extremophiles and the Limits of Life in a Planetary Context", *Frontiers in Microbiology*, 10, 780, 2019). A brief summary is provided on the following pages.

5.1 Temperature

The temperature range within which microbes have been observed to function is**: –20°C ≲ T ≲ 122 °C.**

The most extreme thermophiles, the so-called hyper-thermophiles, grow optimally at temperatures between 80 and 100°C. The highest temperature environment from which a hyper-thermophile has been isolated (122°C, for the archaeon *Methanopyrus kandleri*) is the wall of a black smoker in the Gulf of California at a depth of ~2000 m, where the high pressure ensures that the water remains liquid.

Note that, hyperthermophiles have had to evolve special modifications to their cell membranes, DNA, and proteins in order to survive these high temperatures. The absolute upper-temperature limit to life is unknown, but theoretical considerations suggests that it is likely to be ~150°C.

The lowest temperature known to permit active metabolism in a psychrophile is ~ –20°C, provided water can be kept liquid by suitable dissolved substances (of course, spores, cells, and even some entire animals, can remain dormant at much lower temperatures). The theoretical minimum is thought to be ~ –40°C. Note that cold adaptation also requires special proteins and other modifications that don't work well at higher temperatures, so a particular organism cannot, as far as we know, be both a thermophile and a psychrophile.

5.2 pH

The pH range within which micro-organisms have been observed to function is: **0.0 ≲ pH ≲ 12.5** (although there are environments with negative pH suspected of being inhabited by hyper-acidophiles).

pH values at these extremes would prevent basic cellular biochemistry from occurring, so acidophiles and alkaliphiles must actively maintain an internal pH that is more neutral (pH ~7) than their environment, and this in turn requires specialised membrane structures.

5.3 Salinity

The salinity range within which microbes have been observed to function is**: $0 \lesssim$ (wt% NaCl) $\lesssim$ 35%.**

Salt causes severe osmotic gradients across cellular membranes (that is, water will try to flow from regions of low salt concentration to regions of higher salt concentration, which is capable of exerting a strong, and disruptive, pressure). Nevertheless, extreme halophiles are observed to survive even in brines where the salt concentration is essentially saturated (35 wt% NaCl at 20°C), and may even remain viable in supersaturated brines with up to 50 wt% NaCl (for example in liquid inclusions in salt crystals). Again, special biochemical adaptations are required to mitigate the high external salt concentrations. Note that, because dissolved salts lower the freezing point of water, adaptation to salt-rich environments will enable habitability in cold environments where water would otherwise not be liquid.

5.4 Pressure

The naturally observed range of pressure tolerance is: **$0 \lesssim P \lesssim 1200$ bars**.

Here, the maximum value corresponds to the water pressure at the bottom of Earth's deepest ocean trenches. However, experiments performed with diamond-anvil cells (where small volumes are subjected to high pressures in a laboratory) have determined that some piezophiles can at least tolerate pressures as high as ~20,000 bars and remain metabolically active.

5.5 Radiation

The observed range of radiation tolerance for micro-organisms is: **0 to ~30 kGy.**

Here the Gray (Gy) is the SI unit for the absorption of ionising radiation (1 Gy corresponds to the absorption of 1 Joule of ionising radiation per kg of matter).

Note that an ionising radiation dose of ~5 Gy is generally fatal to humans, so 30 KGy is 6000 times higher.

Examples of radiation tolerant micro-organisms include *Deinococcus radiodurans,* famously found in the cooling waters of nuclear reactors, and the thermophilic bacterium *Thermococcus gammatolerans* (note the names!). These and similar radiation tolerant organisms have evolved efficient DNA repair mechanisms and other strategies to cope with radiation exposure, but need to be metabolically active to make use of them.

5.6 Life's parameter space

We refer to the combination of environmental parameters within which life can exist as life's `parameter space'. Fig. 4 shows a three-dimensional version of life's parameter space in a salinity – temperature – acidity plot (since this diagram was drawn the parameter limits have expanded slightly). Interestingly, the diagram shows that, at least on Earth, halophiles are found in relatively low temperature environments: there are no halophilic hyper-thermophiles.

Such diagrams provide a simple means of assessing whether a particular planetary environment is likely to be habitable. We know that life on Earth can survive within the parameter space, so we would expect that life must also be possible given the same set of parameters on other planets. What we don't know is the extent to which the limits defined by terrestrial life are universal, or merely reflect peculiarities of terrestrial biology.

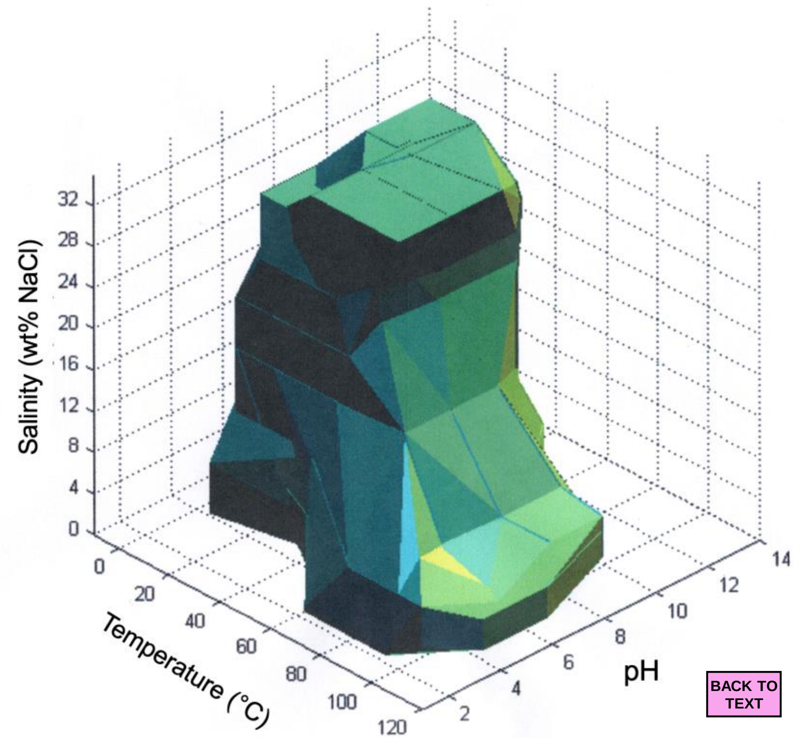

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Fig. 4. A 3-D rendition of life's parameter space, here defined by temperature, pH, and salinity. (Diagram courtesy of Julian Wimpenny and Cristian Picioreanu, University of Cardiff; reproduced with permission).

6. Astrobiologically important examples of extreme environments

6.1 Hydrothermal vents

Deep sea hydrothermal vents were discovered at mid-ocean ridges in 1977. Where the hot water (~350°C) mixes with cold (~2°C) sea water, dissolved minerals are precipitated to form the characteristic 'black smokers' (Fig. 5). One of the major surprises following the discovery of hydrothermal vents was that they support a rich fauna in the complete absence of photosynthesis. Instead, the primary producers are chemoautotrophs, mostly relying on sulphides emitted by the vents as electron donors, e.g:

$$H_2S + CO_2 + O_2 + H_2O \rightarrow \text{“}CH_2O\text{”} + H_2SO_4$$

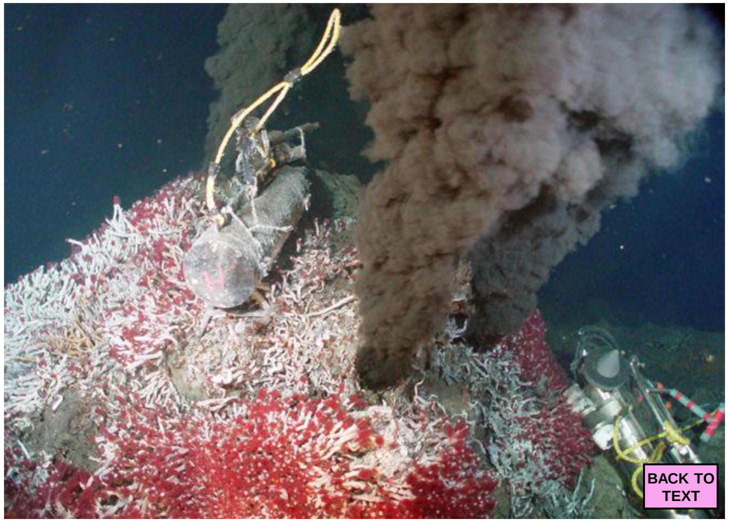

Fig. 5. A 'black smoker' at a deep-sea hydrothermal vent supporting a population of tube worms (NOAA/Public Domain).

The chemosynthetic micro-organisms support a wide variety of 'higher' organisms, and more than 400 animal species have now been identified in hydrothermal vent communities. Many of these animals, including the tube worms (Figs. 1 and 5), are symbiotic organisms, deriving energy and organic compounds from endosymbiotic chemosynthetic (sulphide-reducing) bacteria. An excellent YouTube video on life at hydrothermal vents, produced by the Smithsonian Institution, can be viewed here: https://www.youtube.com/watch?v=6ByT4ponpUQ

From an astrobiology perspective, it is important to point out that these hydrothermal communities are not as independent of the rest of life on Earth as is sometimes claimed, because the main chemo-synthesis reactions rely on dissolved O_2 in the sea water as an electron acceptor.

On the other hand, some anaerobic microbial chemosynthesis does occur, accounting for up to 4% of primary production. In these cases H_2 is the main electron donor, with CO_2, S, SO_4^{2-} and NO_3^{2-} as electron acceptors. For example:

$$\mathbf{4H_2 + CO_2 \rightarrow CH_4 + 2H_2O}$$

Thus, life would still be supported around hydrothermal vents, even in the absence of O_2, it's just that O_2 is so useful that it will dominate proceedings if it is present. This is important when hypothesising the possibility of hydrothermal vents in oxygen-free environments, such as the ice-covered oceans of the outer Solar System (Lecture 9).

6.2 Endolithic habitats

In harsh environments on Earth (e.g. the Antarctic Dry Valleys, where the mean annual temperature is as low as −30°C), bacteria, algae and fungi can survive a few mm beneath the surfaces of rocks. Hence the term 'endolithic' (Fig. 6). This protects them from desiccation, and yet permits sufficient sunlight to penetrate for photosynthesis. For most of the year these organisms lie dormant, but are able to grow during the few weeks in the year when the temperature of their habitat rises above freezing due to absorption of sunlight by the rock surfaces.

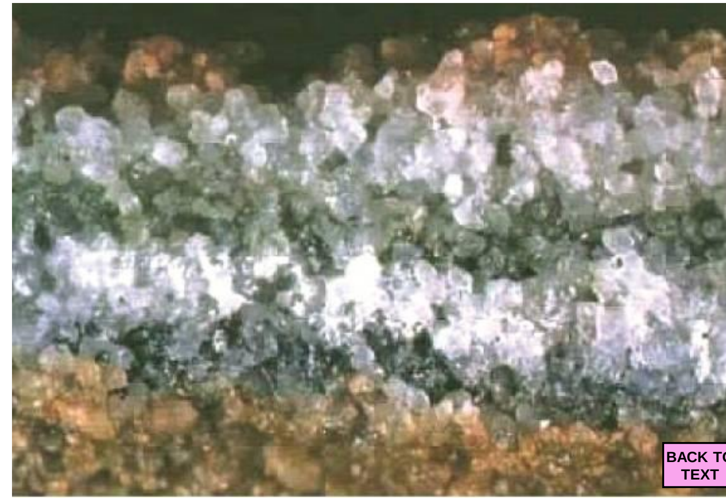

Fig. 6. **Top**: Endolithic community from Antarctica. The specimen is 24 mm wide, The outer few mm are devoid of life. Then, at a depth of about 4 mm is a greenish layer containing algae and/or cyanobacteria. (Image courtesy of J. Hiscox). **Bottom:** Similar endolithic community under a carbonate crust from an alkaline site in the Brecon Beacons (Image: I.A. Crawford).

6.3 Sub-glacial lakes

In 1995 Lake Vostok was discovered in Antarctica (Fig. 7). Lake Vostok is 250 km long, 40 km wide, 400m deep, and under ~3 km of ice. A borehole was been drilled into the lake from the Russian Vostok research station. Microbes have been recovered from the 'accretionary ice' above the lake, which strongly suggests that life is present in the lake and has probably remained undisturbed for between 0.5 and several million years. The drill reached the lake surface in early 2012, but the resulting water was found to be contaminated by kerosene (and associated bacteria) used as the drilling fluid. Biological analysis is on-going, but compromised by contamination issues.

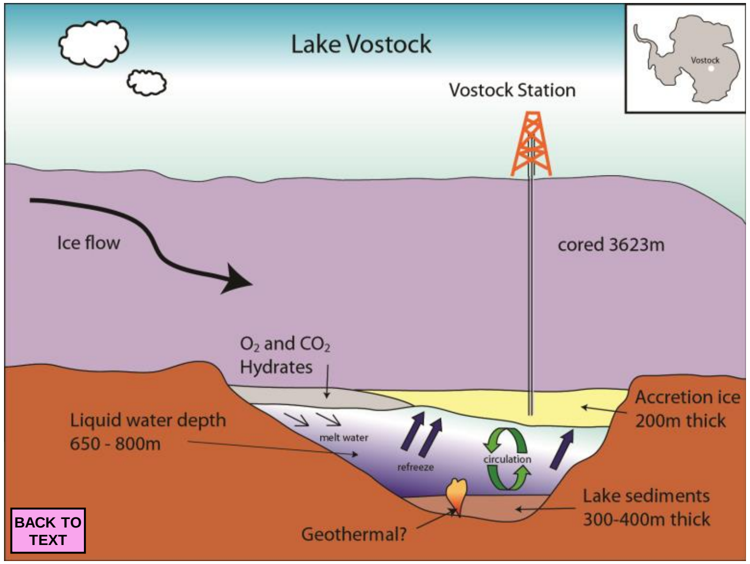

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Fig. 7. Schematic illustration of Lake Vostok. Note the prism of 'accreted ice' that has frozen directly from the lake itself, and within which micro-organisms have been found. The geothermal heat sources are speculative.

Almost 400 Antarctic sub-glacial lakes are now known. A US-led drilling project sampled the smaller and shallower (800m deep) sub-glacial Lake Whillans in 2013. This used 'hot water drilling' to avoid contamination and successfully revealed "a chemosynthetically driven ecosystem inhabited by a diverse assemblage of bacteria and archaea" (B.C. Christner et al., 'A microbial ecosystem beneath the West Antarctic ice sheet', *Nature*, 512, 310, 2014). A UK-led project to drill into subglacial Lake Ellsworth, also using hot water drilling, had to be abandoned for technical reasons in 2012.

Note that these sub-glacial lakes are possible analogues for ancient lakes on Mars, and the possible sub-surface oceans within icy moons (e.g. Europa and Enceladus).

6.4 The ‘hot, deep biosphere’

Micro-organisms have been found living within the pore spaces of sedimentary, and even igneous, rocks. Such organisms have been dubbed ‘lithophiles’, and probably the most significant from an astrobiological perspective are those found at a depth of 1.2 km in the Columbia River Basalts of the north-western USA. These microbes are chemosynthetic methanogens and acetogens:

$$\mathbf{4H_2 + CO_2 \rightarrow CH_4 + 2H_2O} \quad \text{(archaea)} \quad \text{or} \quad \mathbf{4H_2 + 2CO_2 \rightarrow CH_3COOH + 2H_2O} \text{ (bacteria).}$$

The CO_2 is either dissolved in the ground water, or possibly extracted from the rock, while the H_2 is released by a chemical weathering (serpentinization) reaction between ground water and iron-bearing minerals (e.g. olivine and pyroxene) in the basalt. Thus, except for a source of ground water, these organisms are independent of the surface (although their ancestors presumably evolved there). It is thought that similar organisms might survive at depths as great as 4 km in continental crust, or 7 km beneath the ocean floor, where temperature is likely to be the limiting factor.

In principle, such chemosynthetic organisms could support a population of dependent heterotrophs, and such communities have been dubbed SLiMEs (‘Sub-surface Lithoautotrophic Microbial Ecosystems’). In principle, SLiMEs could exist in the crust of any terrestrial planet where water is available (e.g. Mars). On the other hand, it is difficult to see how life could have evolved in such environments, so, if SLiMEs exist on other planets, they have probably migrated downwards from the surface.