A physicist’s foray into biology

A habitat for psychrophiles in deep Antarctic ice

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Eutectic phase diagram

Microbes live in liquid phase

![Eutectic phase diagram](image1)

![Microbes live in liquid phase](image2)
Cold origin of life on Earth and Mars

- 1-D liquid veins in ice concentrate reactants, increase encounter rate of biomolecules, and avoid hydrolysis, thus greatly increasing polymerization rate.
- Stan Miller et al. (2006) concentrated NH$_4$CN in ice by eutectic freezing at -78°C. After 27 years ice had turned dark due to synthesis of pyrimidines, purines, and glycine in veins.
- Kanavarioti et al. (2001) formed oligo-uridylates up to 11 bases long from ImpU within days at -18°C in frozen solution. Veins were imaged with a dye.
In absence of $^{238}$U and $^{232}$Th, microbes live $>10^6$ yrs in glacial ice.

Habitat 1: liquid veins

Habitat 2: metabolism in aerosols

Habitat 3: clay grains in Greenland basal ice and in West Antarctic ice
Habitat 3: sub-nm layer of “unfrozen water” coats microbes on surfaces of clay grains: source of energy, nutrients, and fluidity.

Curves give theory:

freezing point of $\text{H}_2\text{O}$ lowered by solute ions + van der Waals attraction + Coulomb interaction with charges on surface

unfrozen water fraction

Depressed freezing temperature [degrees C]
Habitat 4: Small molecules diffuse in ice fast enough to maintain metabolism via redox reactions at cell membranes. At -32ºC a 40 fg microbe undergoes ~1 redox reaction per week. Strict anaerobes such as methanogens coexist with aerobes when frozen in ice.
Excess methane in lowest 90 m of Greenland ice

Stained cells: excesses at same depths; origin in wetland below glacial ice.

\textit{In-situ} metabolism by methanogens accounts quantitatively for excess methane!

Syto-23 stain
(our group, 2005)

F420 co-enzyme in methanogens → autofluorescence
(Tung et al., 2006)
Metabolic rate for immobilized cells:

\[
\text{Metabolic rate} = \frac{Y}{n \cdot m \cdot t}
\]

- \(Y\) = yield of \(\text{CH}_4\) or \(\text{N}_2\text{O}\)
- \(n\) = microbial concentration
- \(m\) = carbon/cell
- \(t\) = gas retention time

Microbes in ice cannot move or grow. They use metabolic energy only to repair spontaneous damage; not damage due to \({}^{232}\text{Th}\) and \({}^{238}\text{U}\).
With a 224-nm laser we map autofluorescence of Trp and Chl in microbes at mm depth intervals down multi-km-deep ice cores.
If we use a narrow (200 µm) laser beam, we see large fluctuations in Trp autofluorescence ⇒ microbes + dust transported to ice in bursts.
Silty, basal ice at depth 3044 m in Greenland at -9°C:

acetate, formate, phenol, humics, … in unfrozen water

Fe-reducing bacteria: acetate$^-$ + Fe$^{3+}$ \(\rightarrow\) Fe$^{2+}$ + H$_2$ + CO$_2$  

Phenols and humics in silty ice serve as electron shuttles.

Electrons hop from Fe$^{3+}$ to Fe$^{3+}$ by diffusion in basal planes.
Ice from 6 drill sites where we map vertical distribution of tryptophan (an autofluorescent amino acid) and chlorophyll.
Polar biologists focus on genomics and proteomics, not on fluxes and sources. Statistics on cell concs. are poor.
Microbial cells from Vostok glacial ice at 3501 and 3520 m depth and from ice accreted from subglacial Lake Vostok at ≥3540 m [S. Rogers].

Fluorescence images give live/dead fractions:

Red: ~35% dead cells based on intracellular DNA staining.

Green: ~25% viable cells based on membrane integrity.

Orange: ~40% ambiguous.

Both eucarya and bacteria are seen at all depths.
With ~1 mm beam spot, we get a smooth dependence of intensity on depth. Steep decrease down to 100 m survival of fittest.
Δ\(G_r\) must be < -10 kJ/mol \(H_2\) for methanogenesis via \(4H_2 + CO_2 \rightarrow CH_4 + 2H_2O\). At 15 ppm \(H_2\) in Mars atmosphere, methanogens can grow only at < 0°C.

\[ [H_2] = 10^{-8.4} \text{ M in Mars atmosphere} \]
Using metab. rate $R(T)$ for immobilized cells,

$$\text{CH}_4 \text{ yield} = R(T) \ n \ m \ t$$

$n = \text{microbial conc.}$
$m = \text{carbon/cell}$
$t = \text{burst duration}$

E.g., for $T = 0^\circ \text{C}$ at source, $t = 1 \text{ mo.}$, and $m = 40 \text{ fg C per cell}$, we require $n = 1 \text{ cell/cm}^2$ in source thickness 10 m, or 0.1 cell/cm$^2$ in 100 m.