A physicist's foray into biology

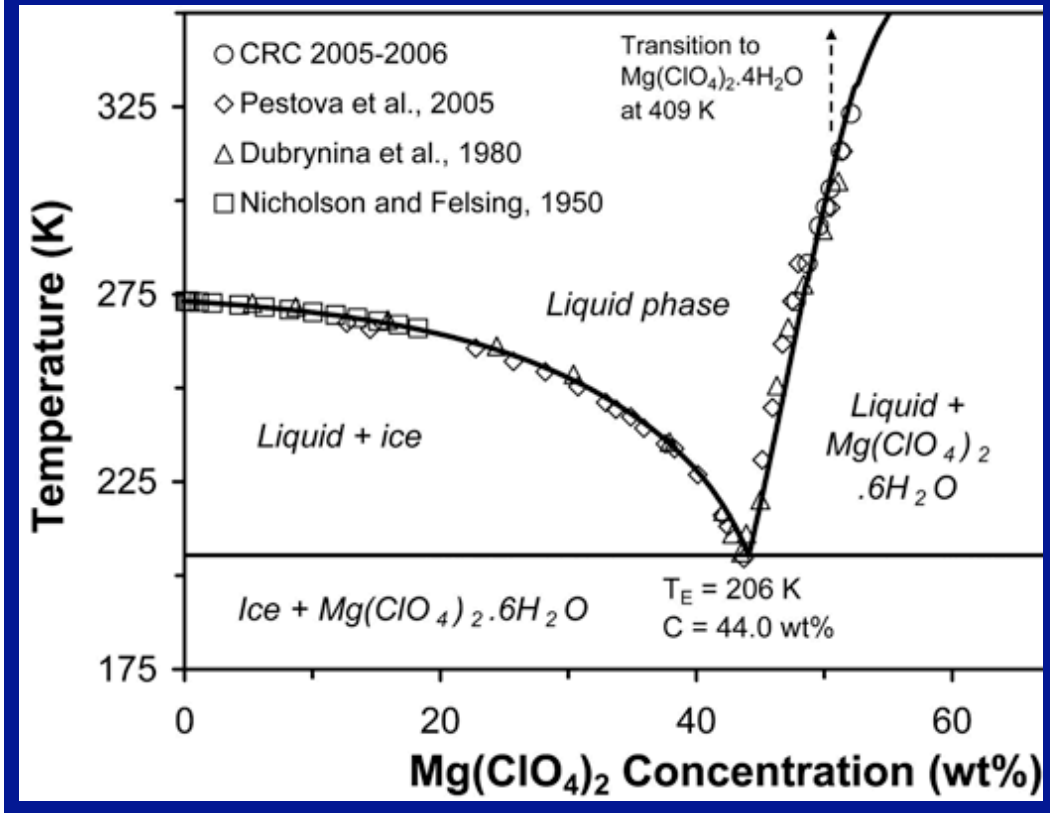
A habitat for psychrophiles in deep Antarctic ice

P. Buford Price*

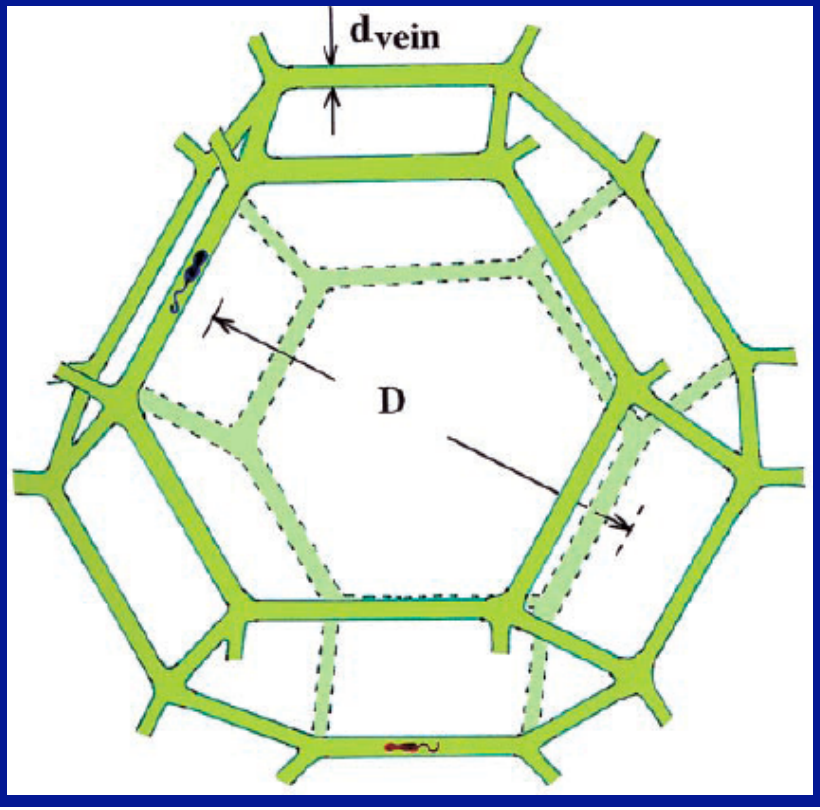
Physics Department, University of California, Berkeley, CA 94720

Contributed by P. Buford Price, November 29, 1999

Eutectic phase diagram



Microbes live in liquid phase

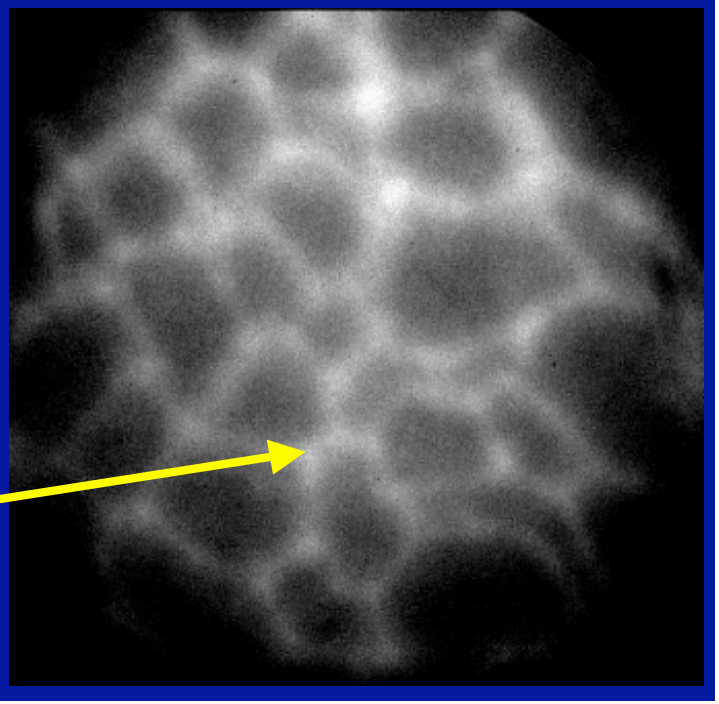


Mars

• 1-D liquid veins in ice concentrate reactants, increase encounter rate of biomolecules, and avoid hydrolysis, thus greatly increasing polymerization rate.

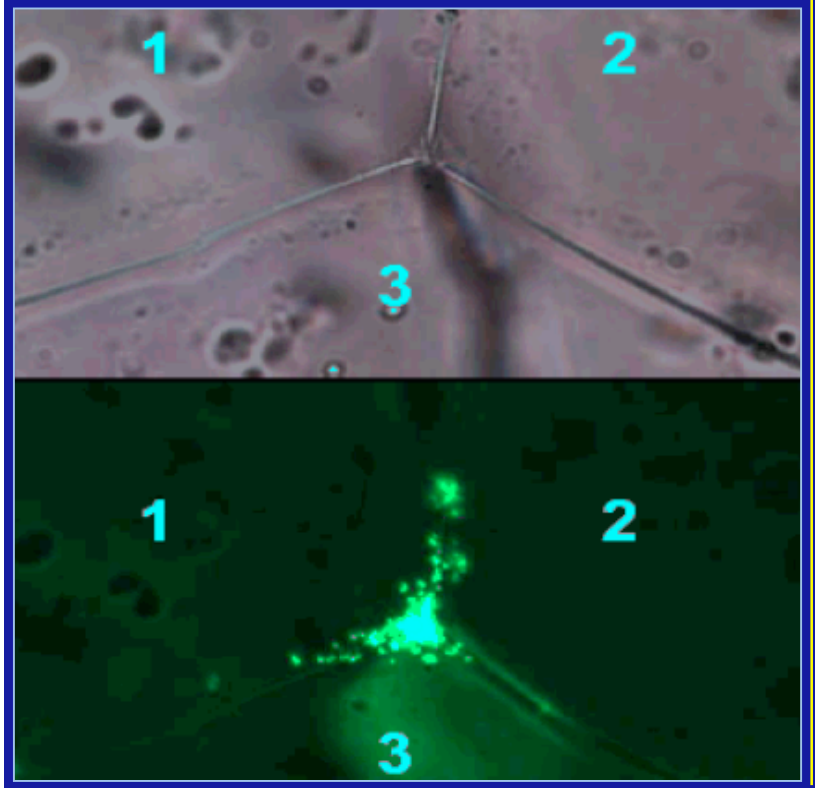
• Stan Miller et al. (2006) concentrated NH_4CN in ice by eutectic freezing at -78°C. After 27 years ice had turned dark due to synthesis of pyrimidines, purines, and glycine in veins.

• 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.

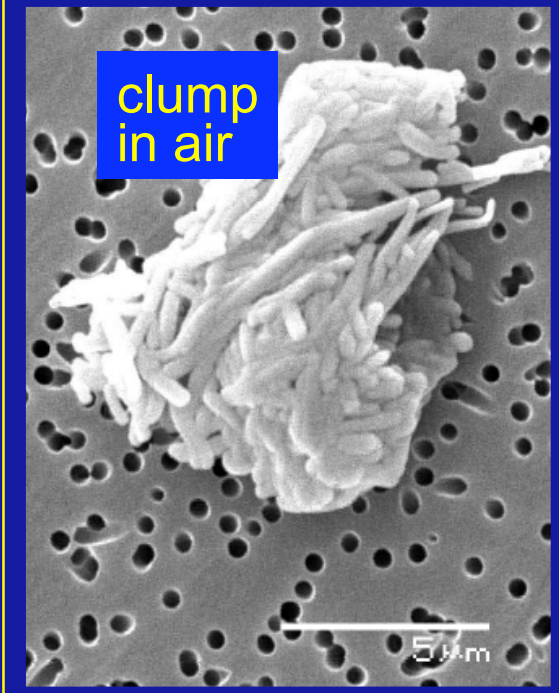


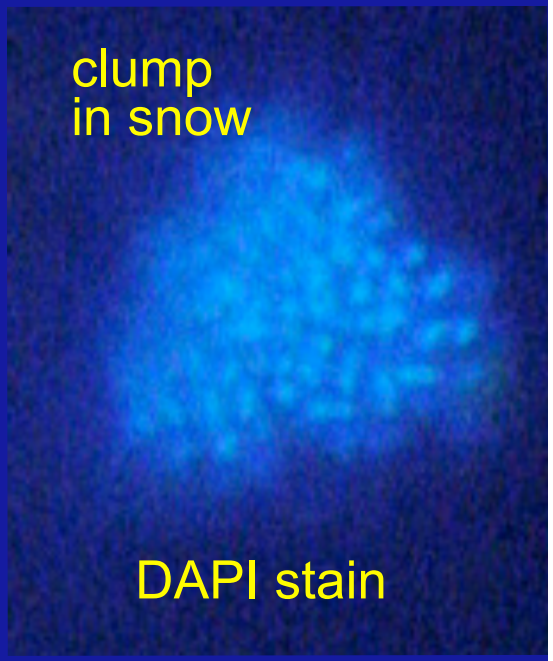
In absence of ^{238}U and ^{232}Th, microbes live >10^6 yrs in glacial ice.

Habitat 1: liquid veins

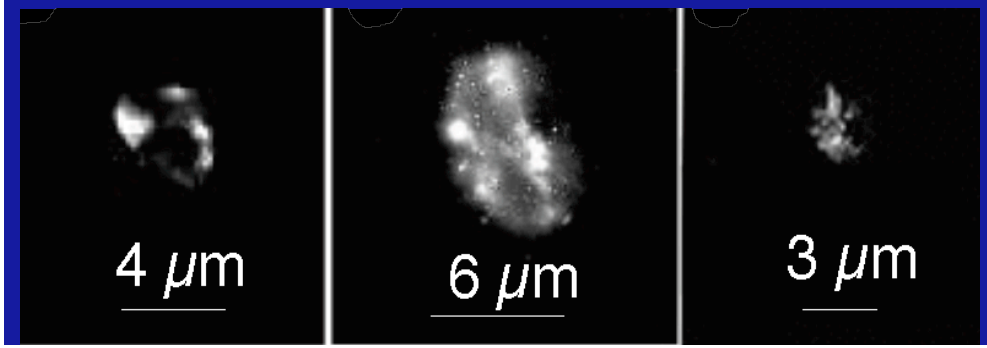


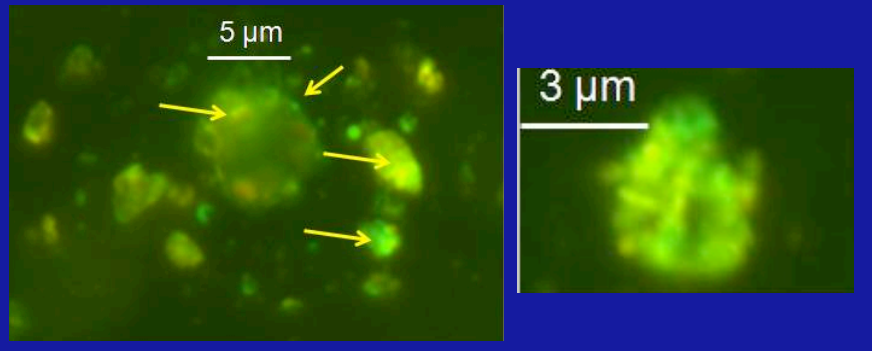
Habitat 2: metabolism in aerosols



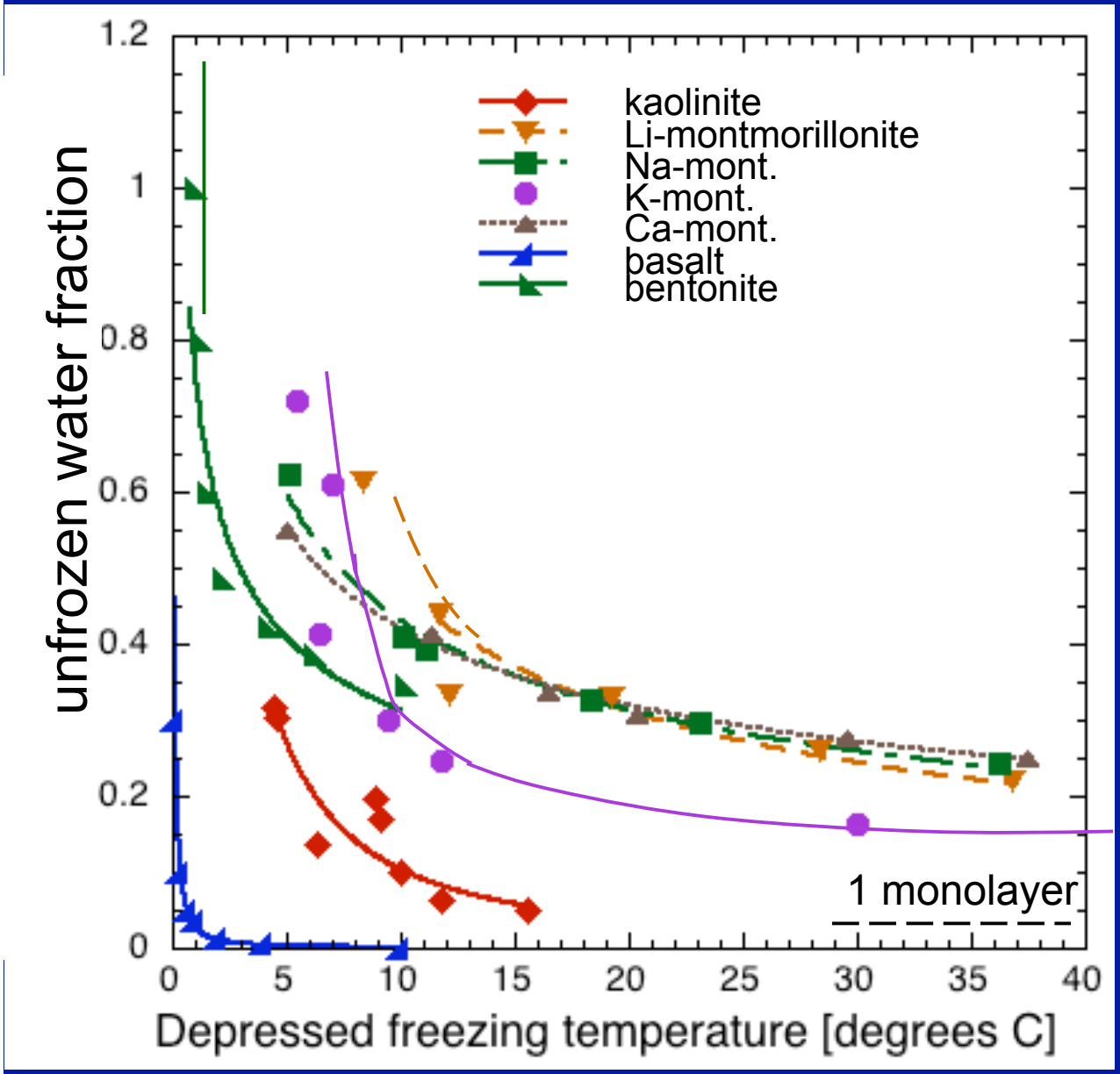


Habitat 3: clay grains in Greenland basal ice and in West Antarctic ice





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 H_2O lowered by solute ions

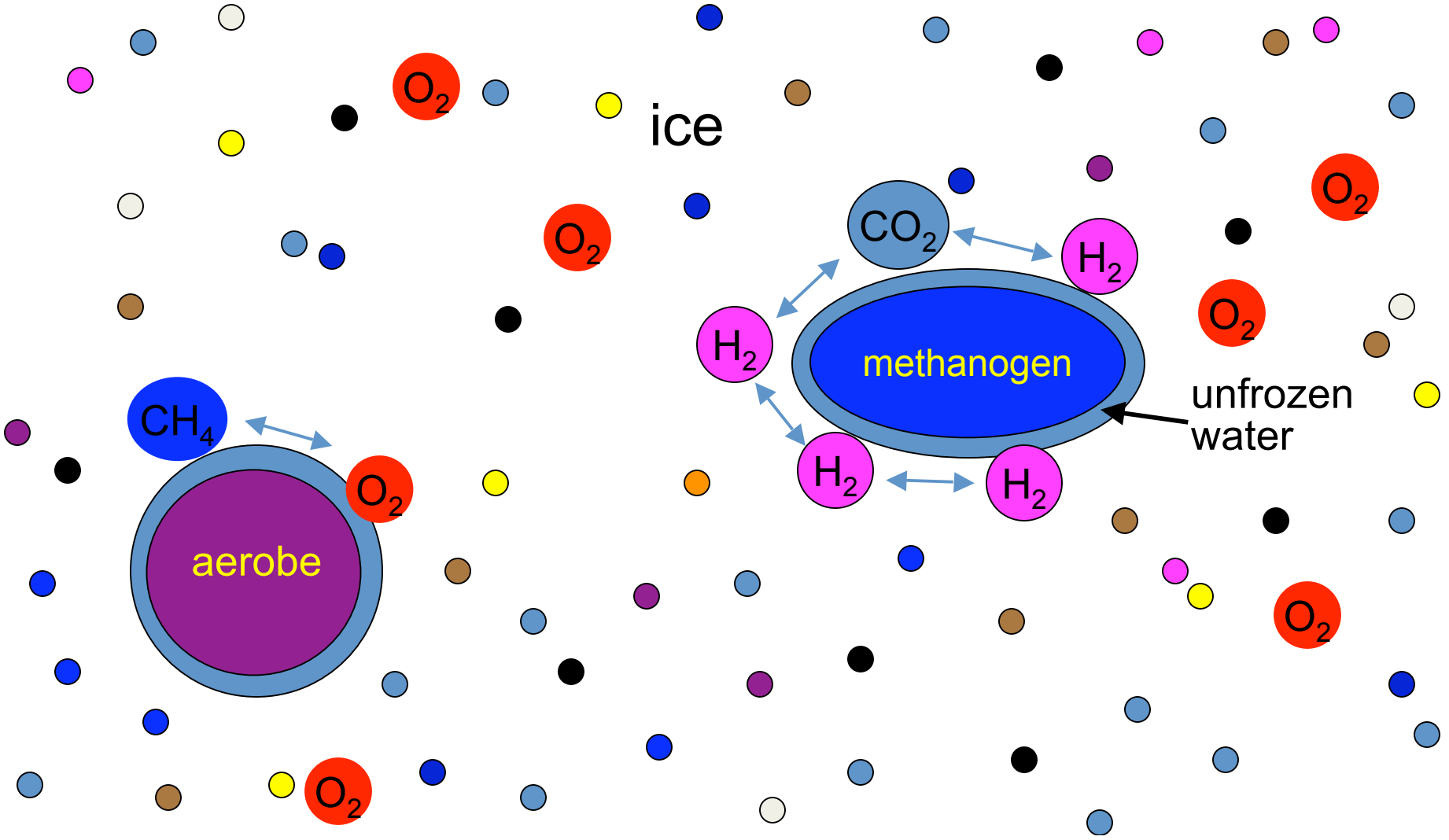
+

van der Waals attraction

+

Coulomb interaction with charges on surface

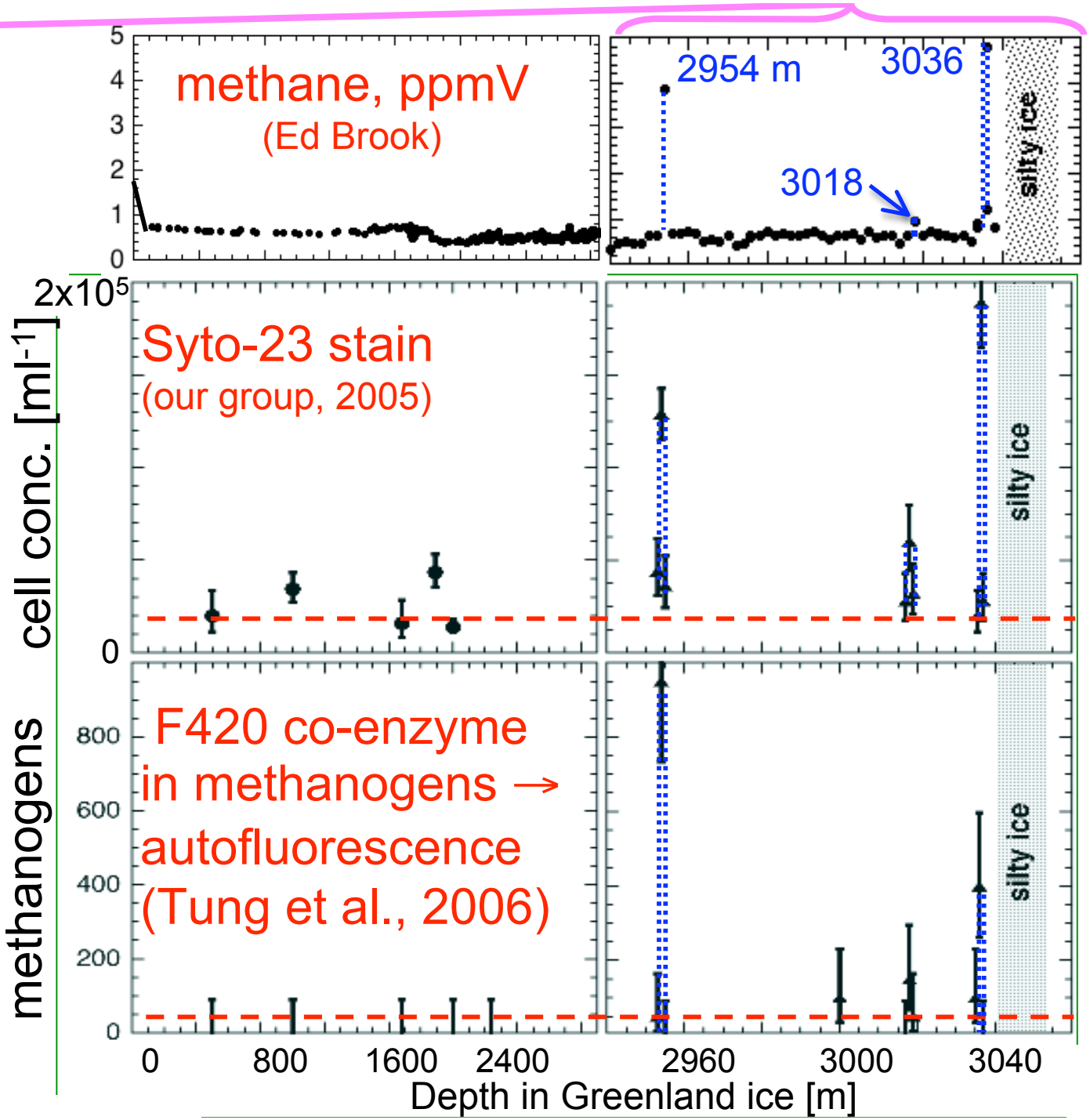
Habitat 4: Small molecules diffuse in ice fast enough to maintain metabolism *via* redox reactions at cell membranes. At -32ºC a 40 fg microbe undergoes ~1 redox reaction per week. Strict anaerobes such as methanogens coexist with aerobes when frozen in ice.

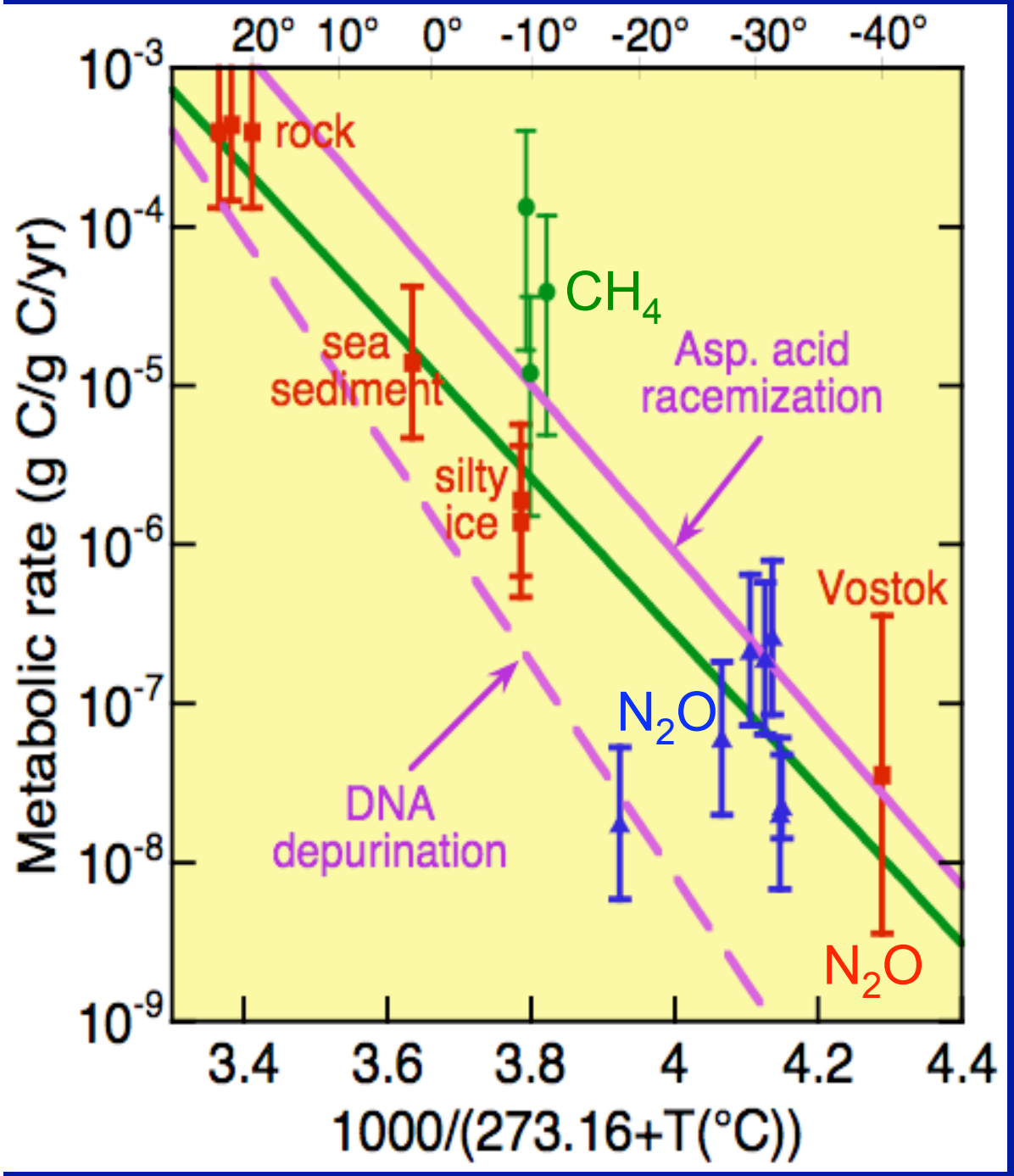


Excess methane in lowest 90 m of Greenland ice

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

in-situ metabolism by methanogens accounts quantitatively for excess methane!





Metabolic rate for immobilized cells:

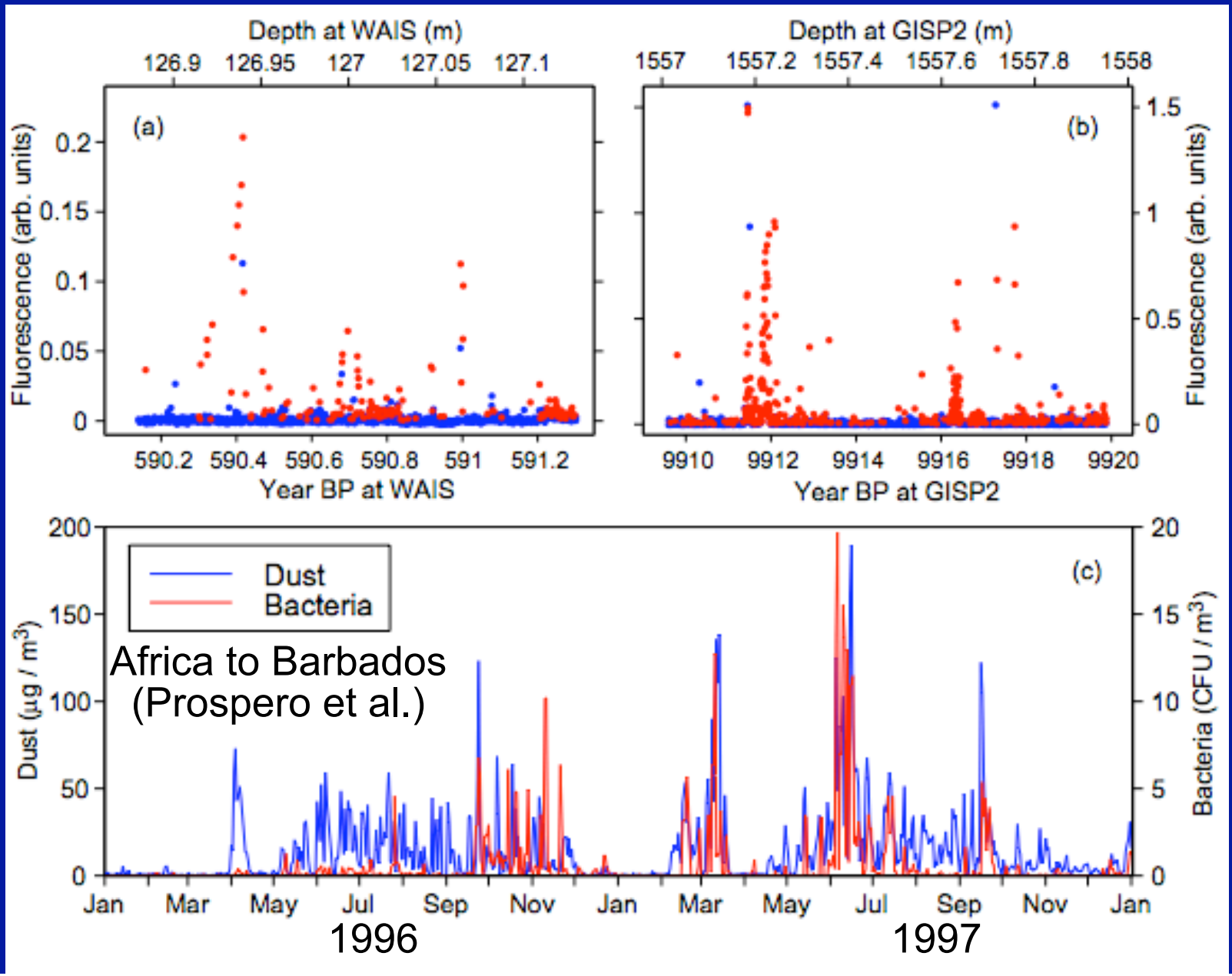
$$\text{Metabolic rate} = \frac{Y}{n\,m\,t}$$

Y = yield of CH_4 or N_2O
n = microbial conc.
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}Th and ^{238}U

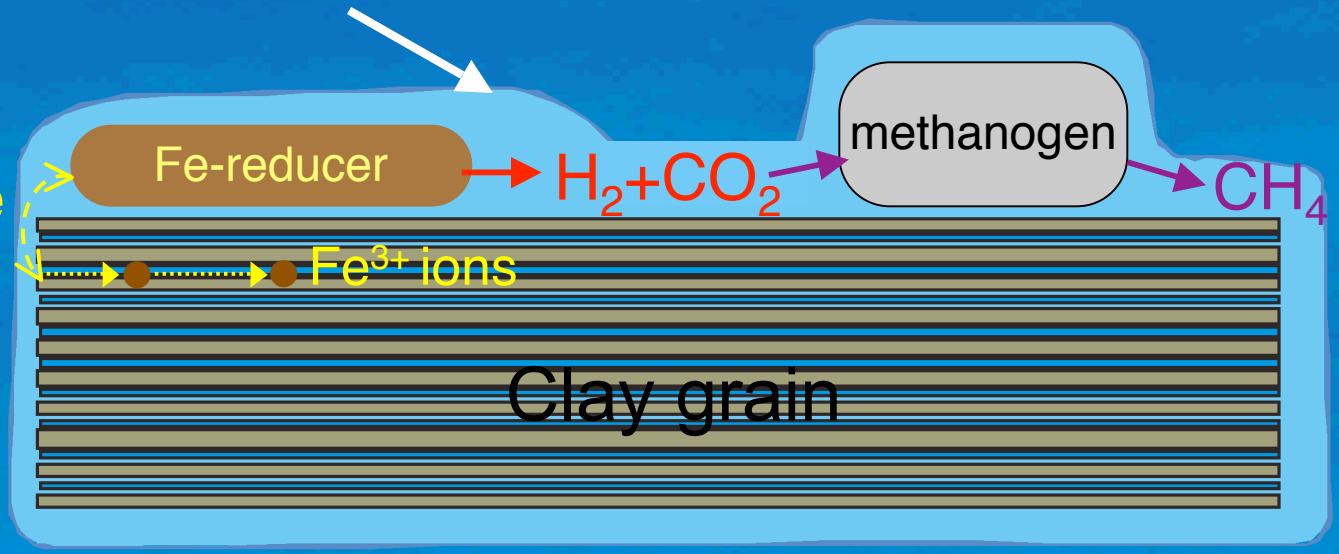
With a 224-nm laser we map autofluorescence of Trp and Chl in microbes at mm depth intervals down multi-km-deep ice cores.

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 -9ºC:

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

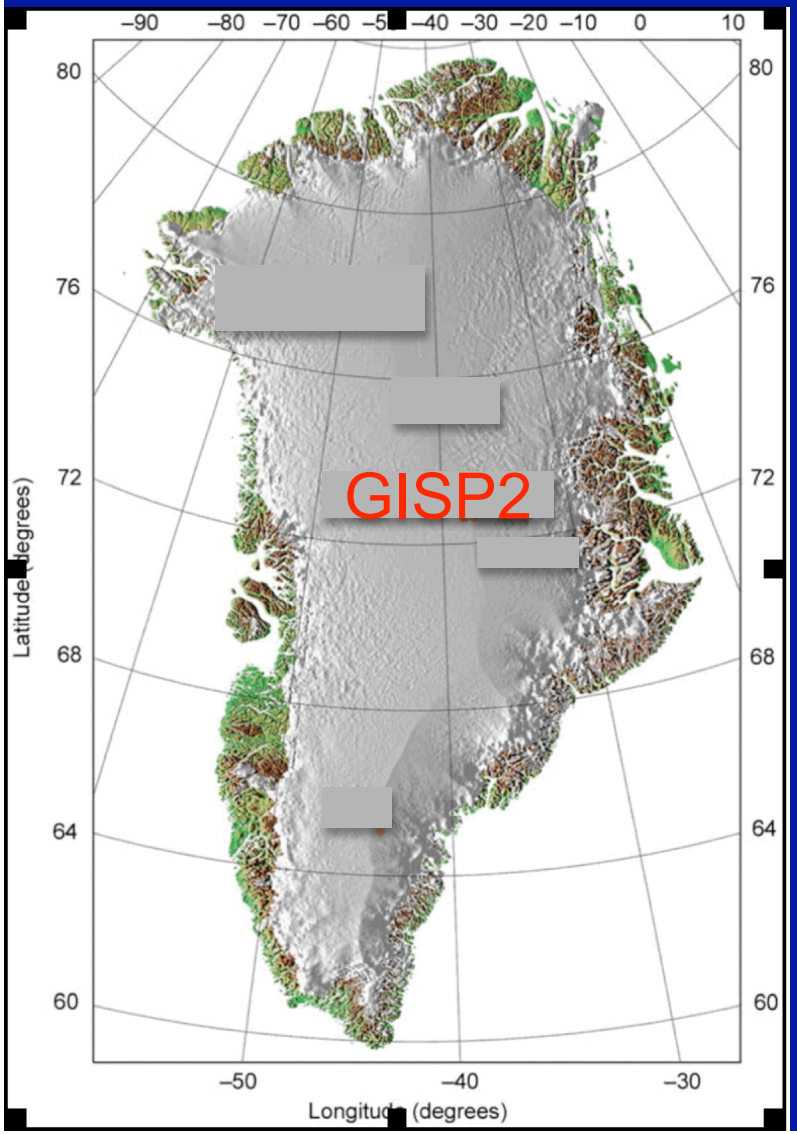


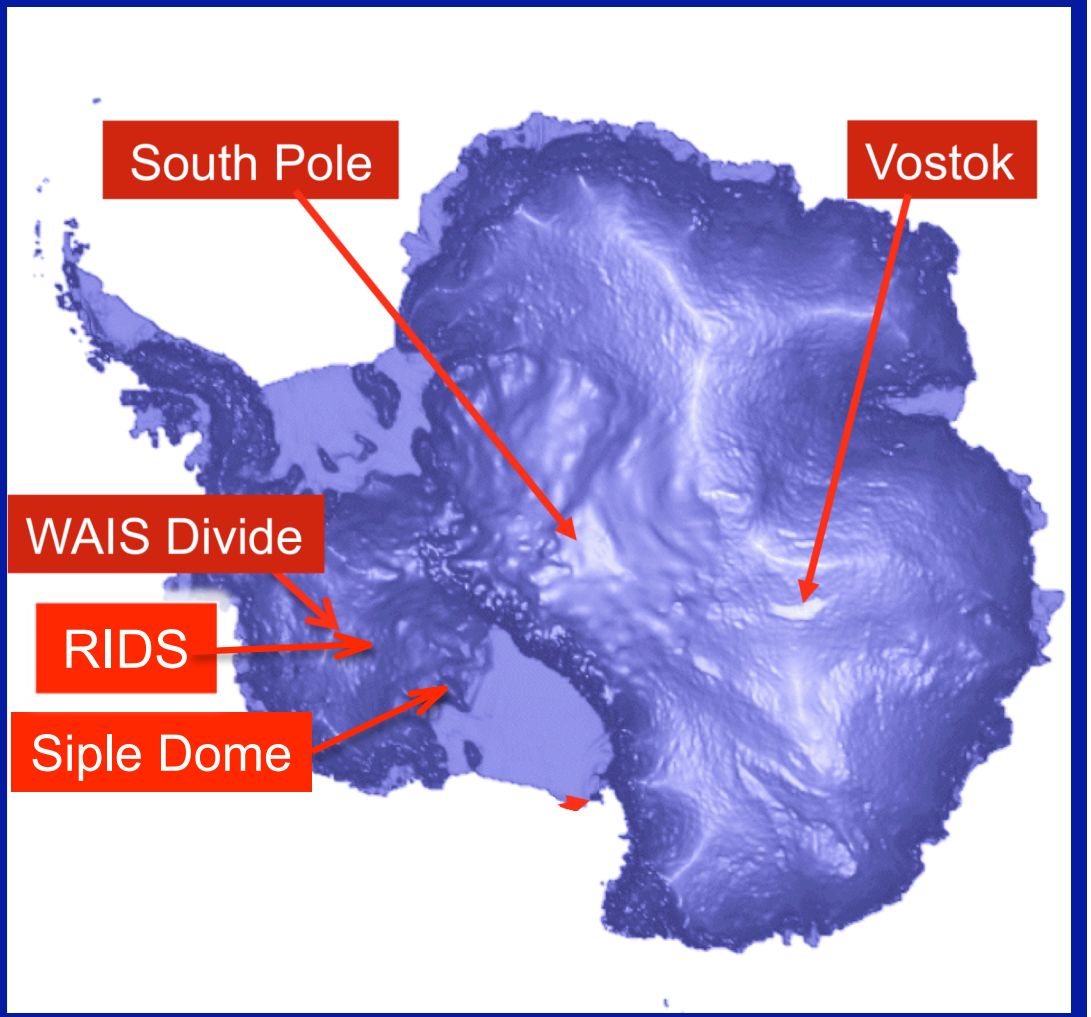
Fe-reducing bacteria: $acetate^- + Fe^{3+} \xrightarrow{shuttle} Fe^{2+} + H_2 + CO_2$

Phenols and humics in silty ice serve as electron shuttles.

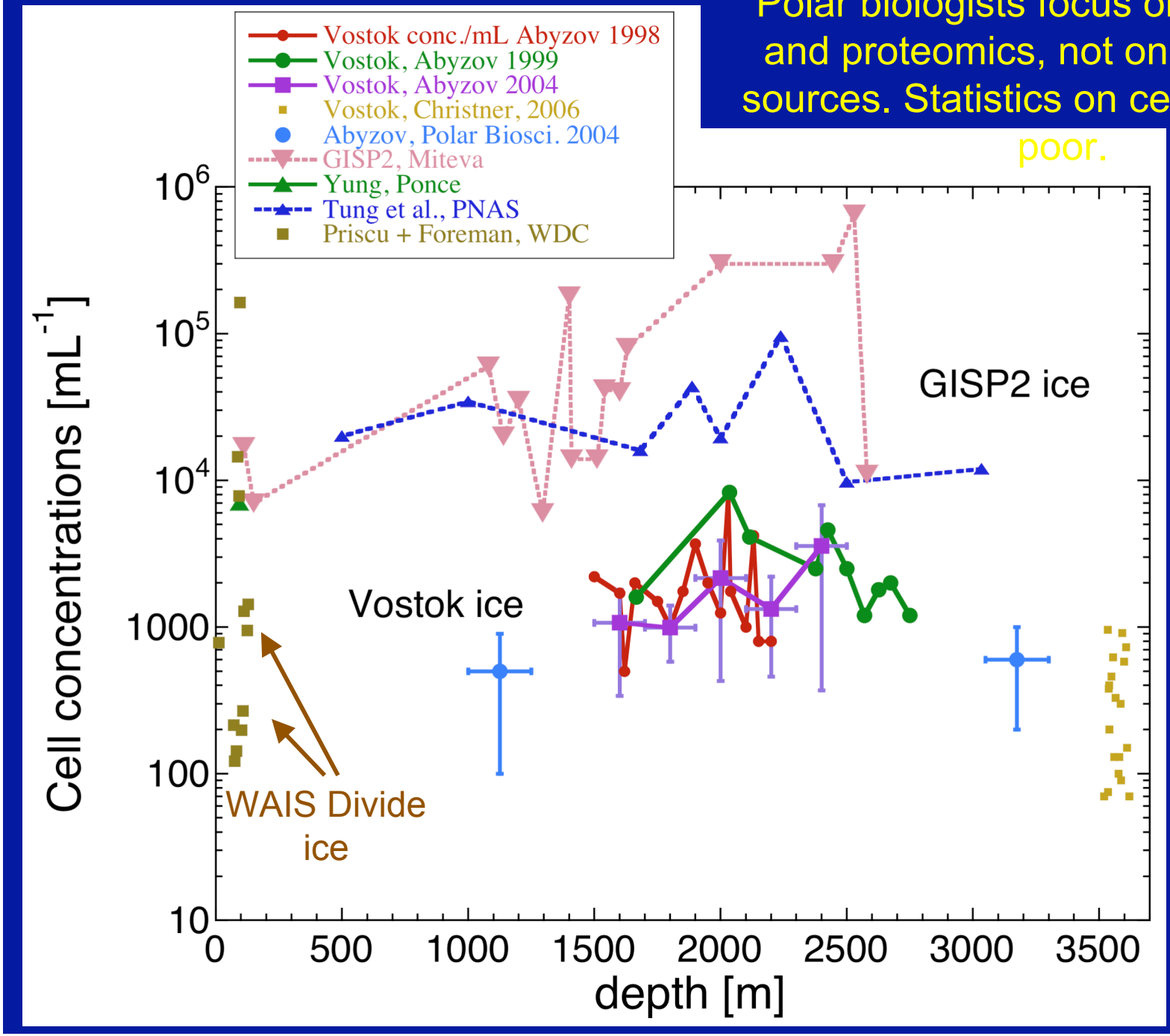
Electrons hop from Fe^{3+} to Fe^{3+} by diffusion in basal planes.

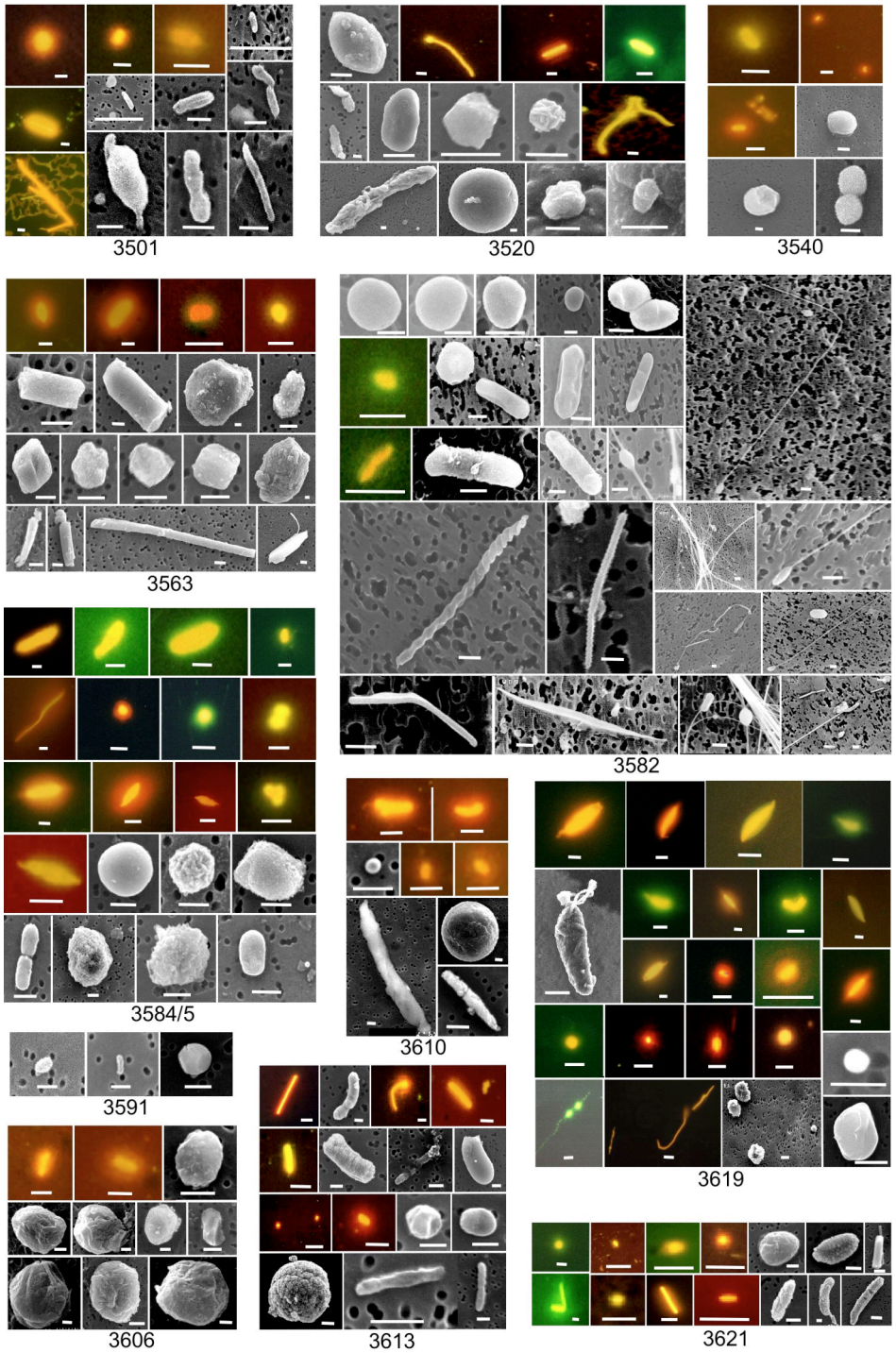
Ice from 6 drill sites where we map vertical distribution of tryptophan (an autofluorescent amino acid) and chlorophyll.





Polar biologists focus on genomics and proteomics, not on fluxes and sources. Statistics on cell concs. are poor.



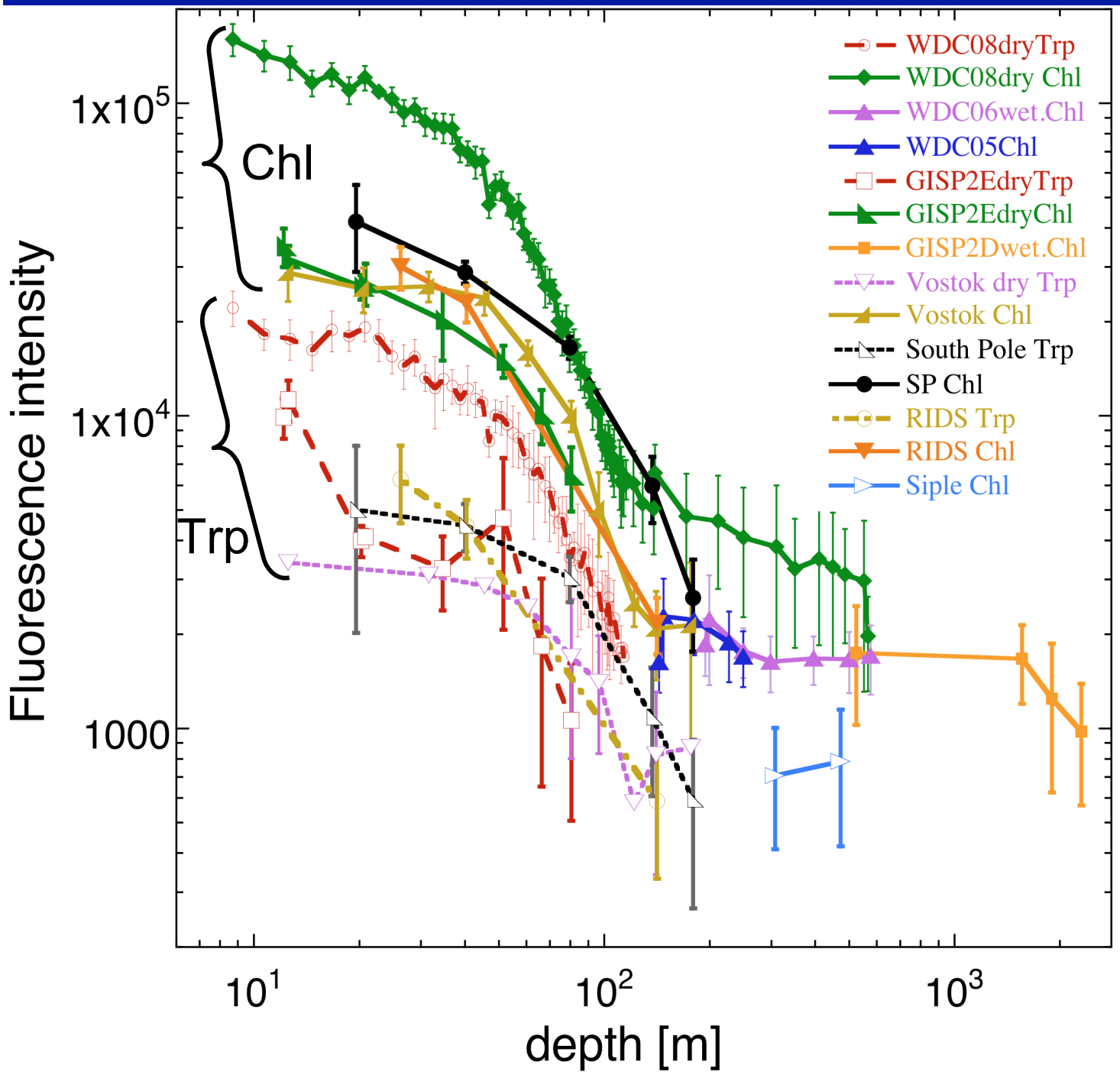


Microbial cells from Vostok glacial ice at 3501 and 3520 m depth and from ice accreted from subglacial Lake Vostok at ≥3540 m [S. Rogers].

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.

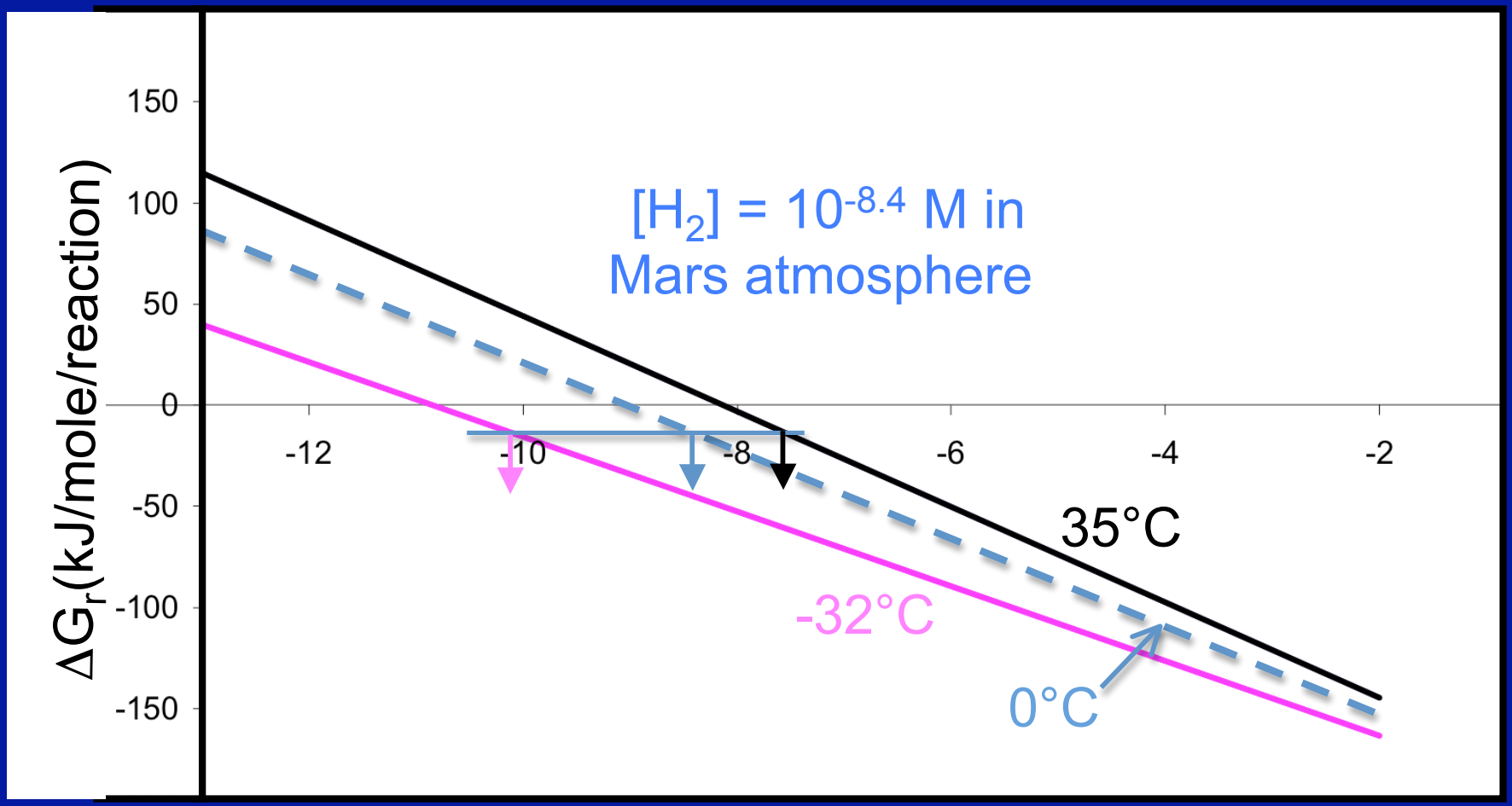
Both eucarya and bacteria are seen at all depths.

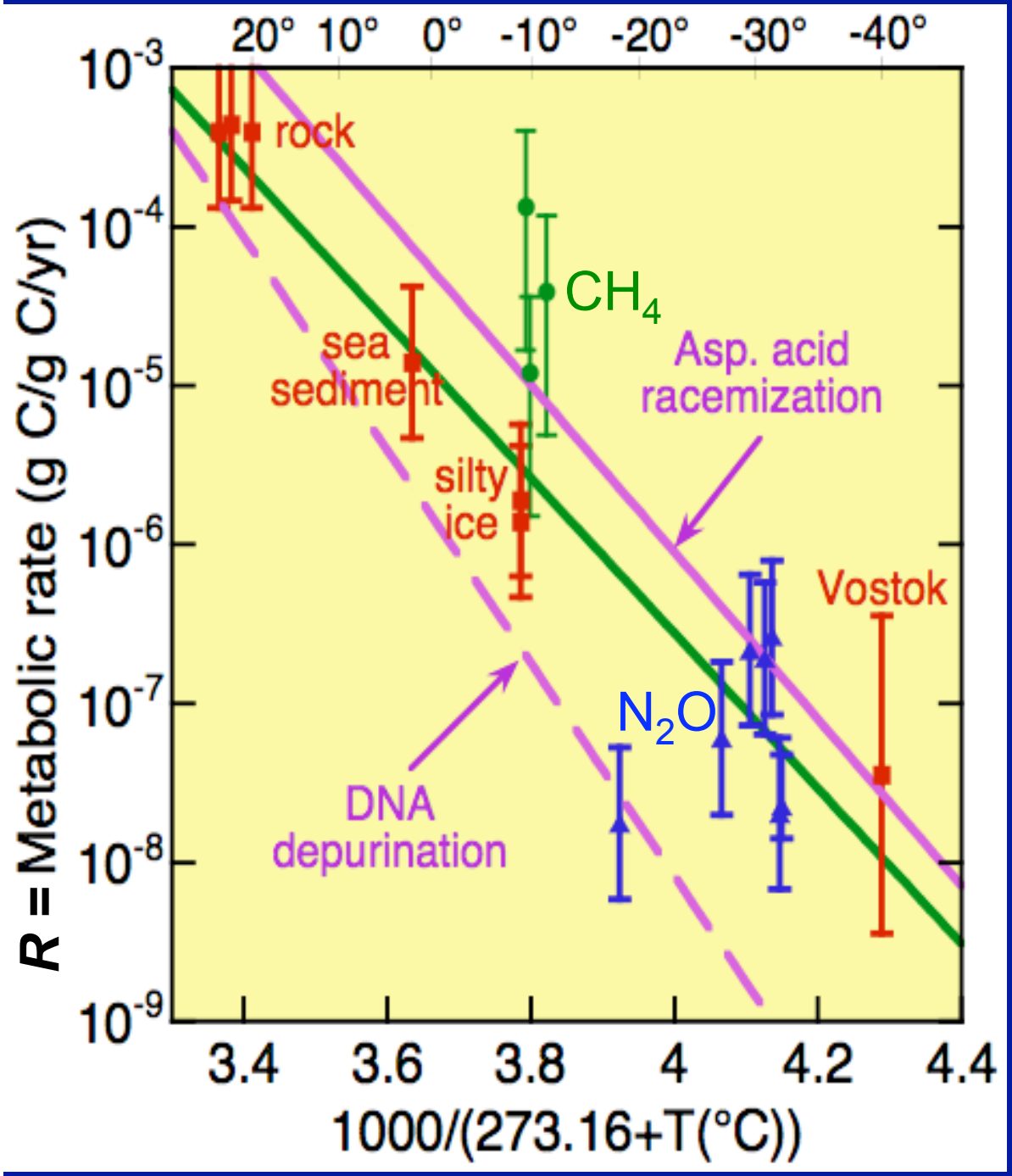


With ~1 mm beam spot, we get a smooth dependence of intensity on depth.

Steep decrease down to 100 m Þ survival of fittest.

ΔG_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.





Using metab. rate $R(T)$ for immobilized cells,

CH_4 yield = $R(T)\ n\ m\ t$

n = microbial conc.
m = carbon/cell
t = burst duration

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