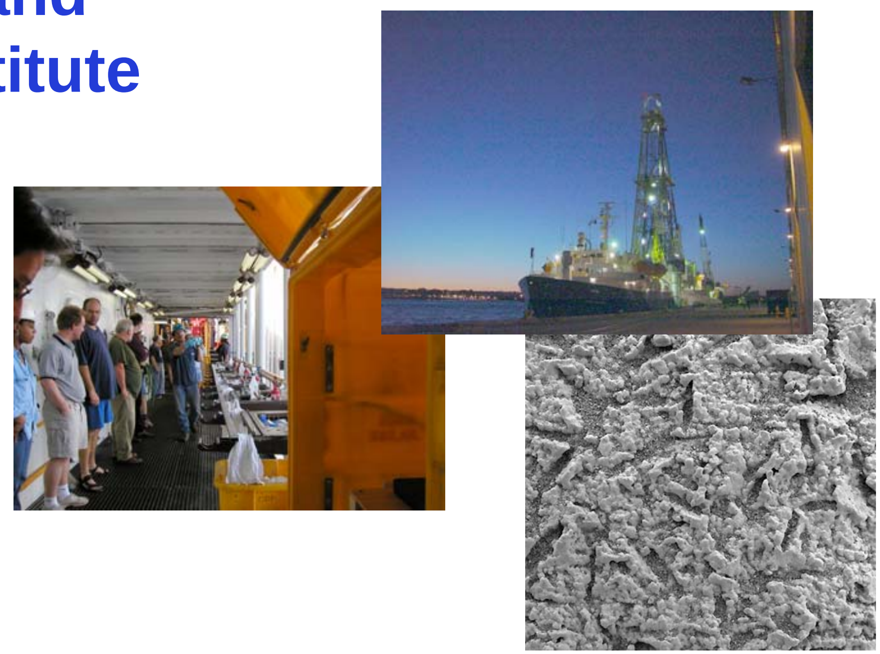
Life in the Deep Subsurface

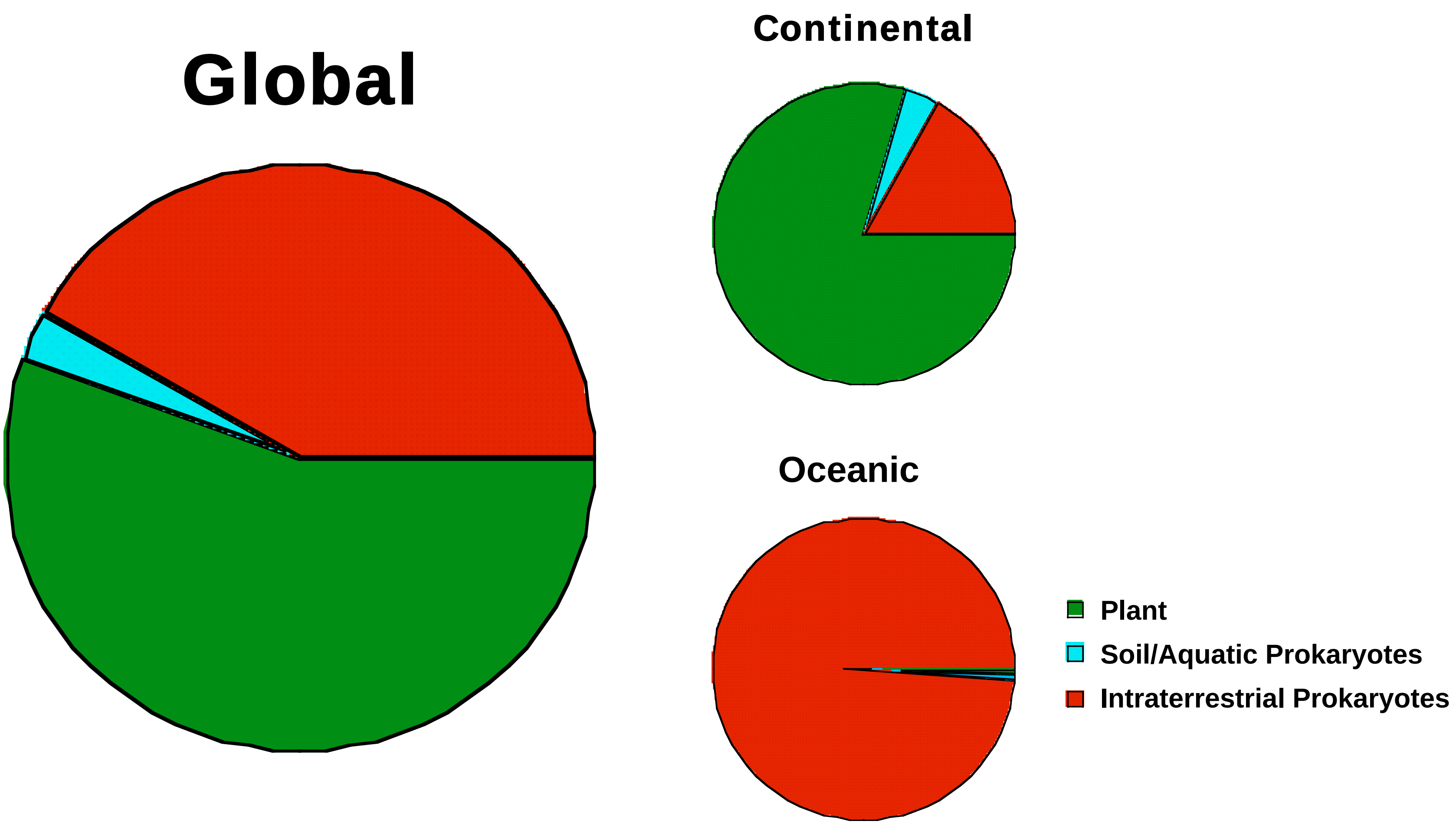
Steven D'Hondt
University of Rhode Island
NASA Astrobiology Institute



Some key questions

- *How big is Earth's subsurface biosphere?*
- *Where does it live?*
- *What is its composition?*
- *What are its principal sources of energy?*
- *To what extent is it independent of the surface world?*

The standard biomass estimate



Whitman et al., 1998, *PNAS*.

Microbes in deep sediments

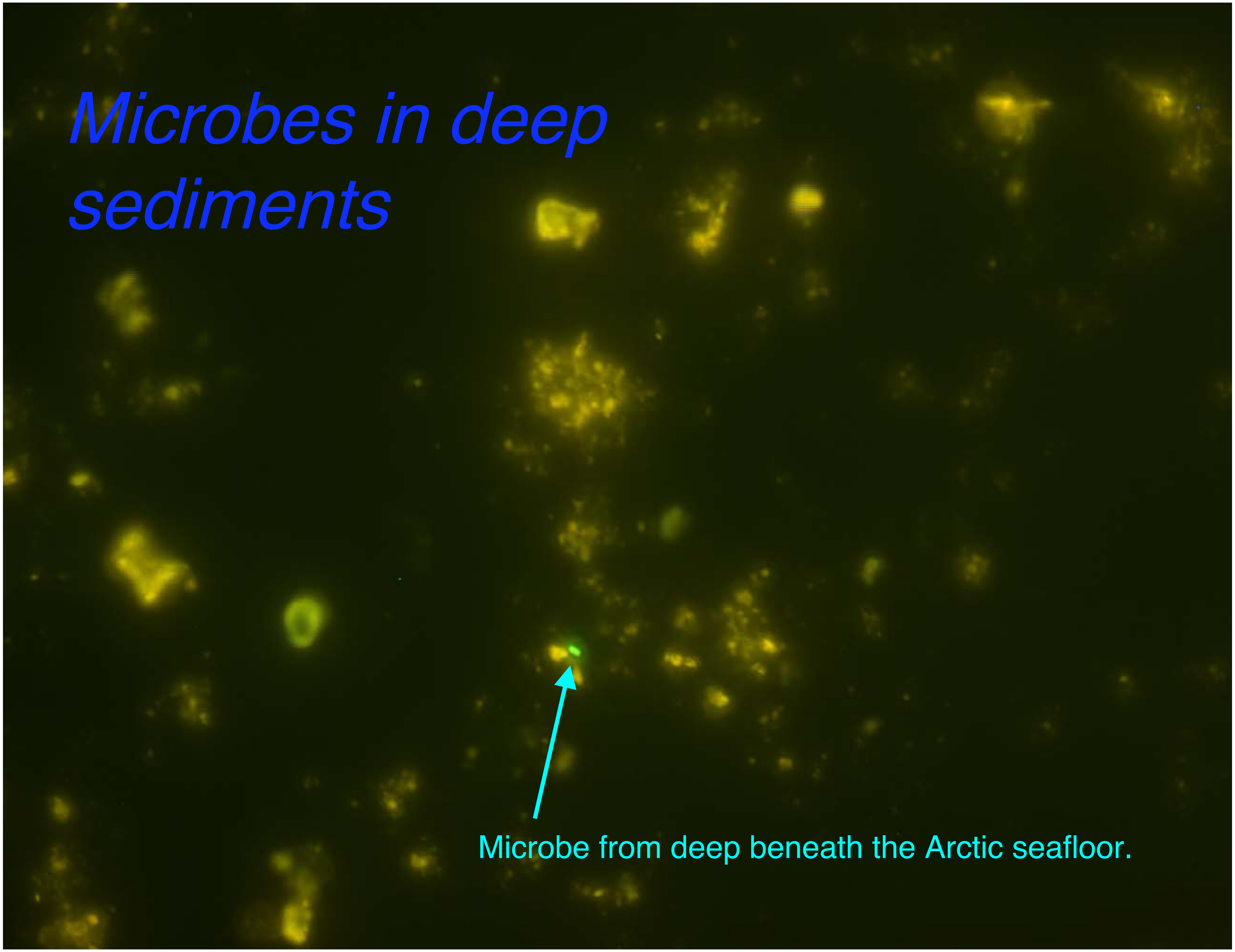
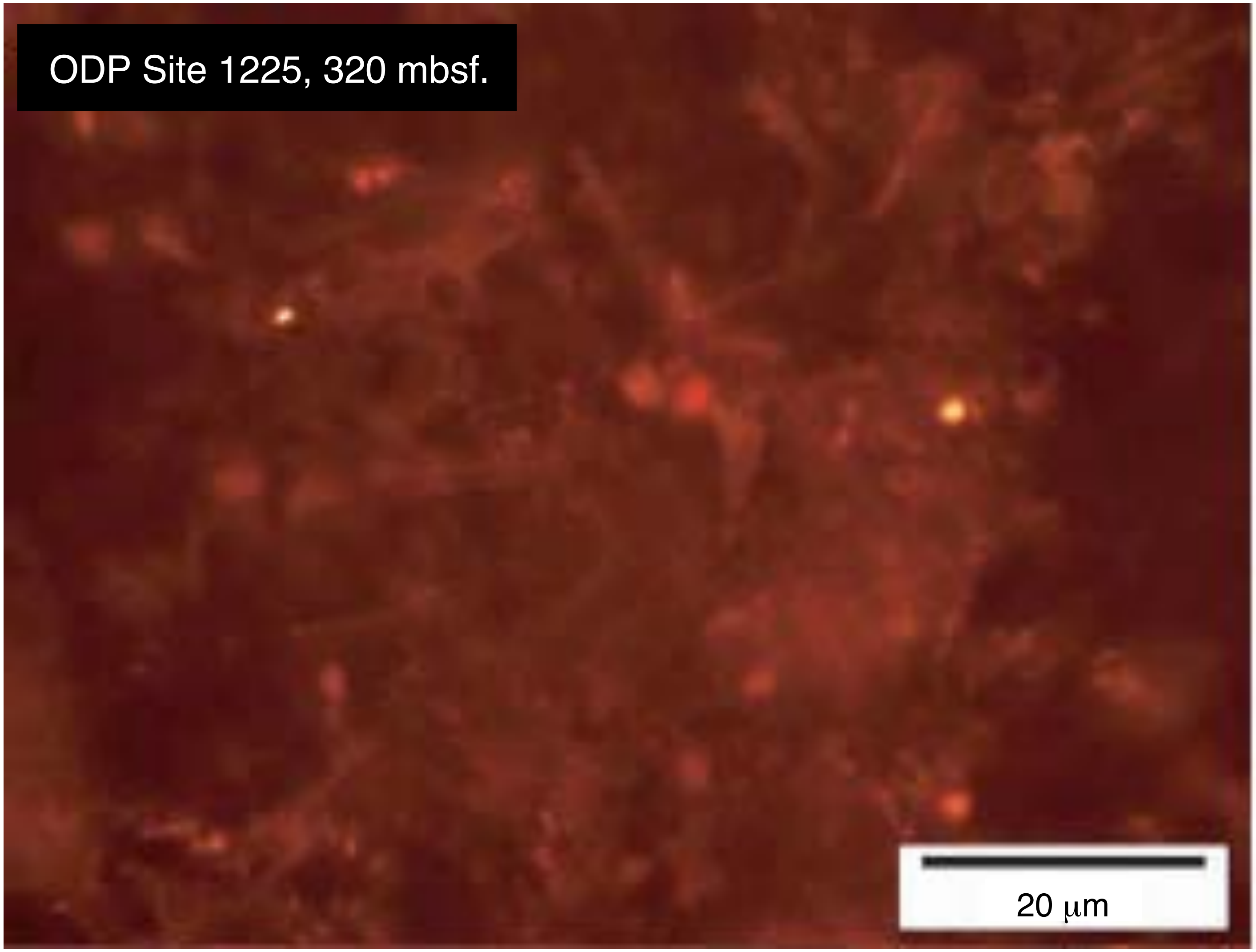


Photo courtesy of D.C. Smith, NAI URI team.

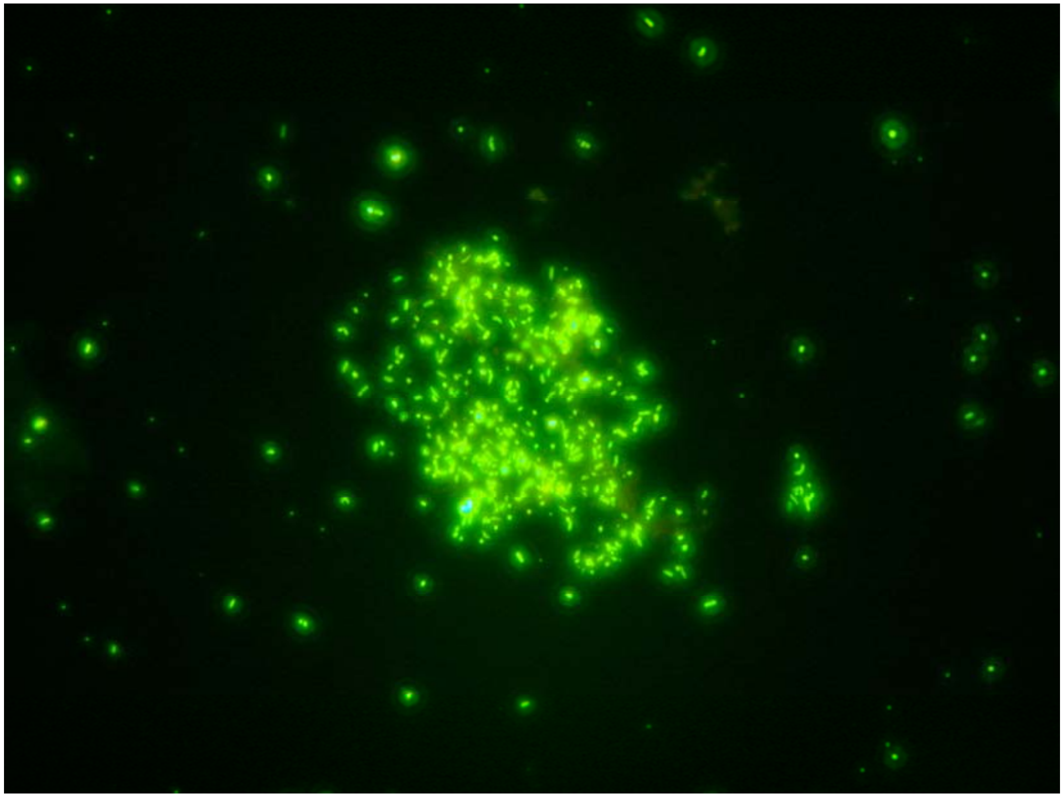
Some are alive

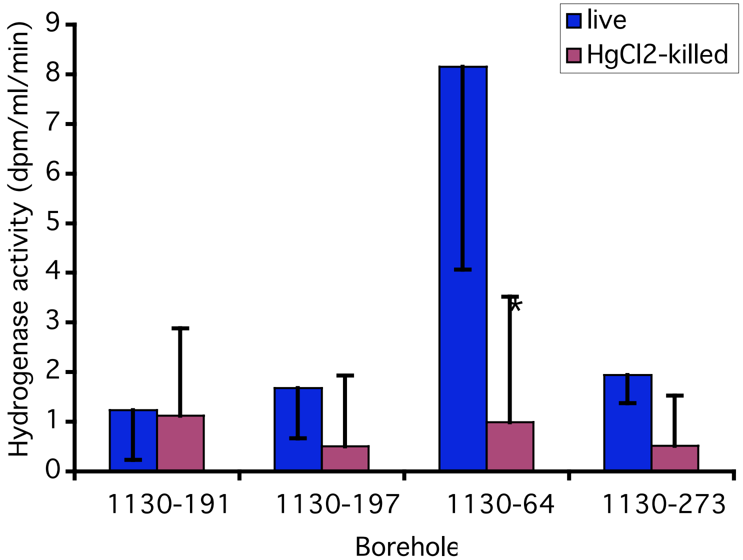


Schippers et al., 2005, *Nature*.

Prokaryotes in deep mines

Microbes from an 1130-m deep borehole (1130-64) at Lupin gold mine (Canada), sampled during a 2005 expedition organized by the NAI IPTAI Team (stained with Cyber Green). The presence of different morphologies suggests a diverse microbial community.





Microbes from this sample exhibited significant hydrogenase activity (Error bars are 95% confidence intervals).

This may be the first direct assay of microbial activity at such a great depth.

Photo and data courtesy of B. Soffientino, NAI URI team.

How deep does Earth's life go?

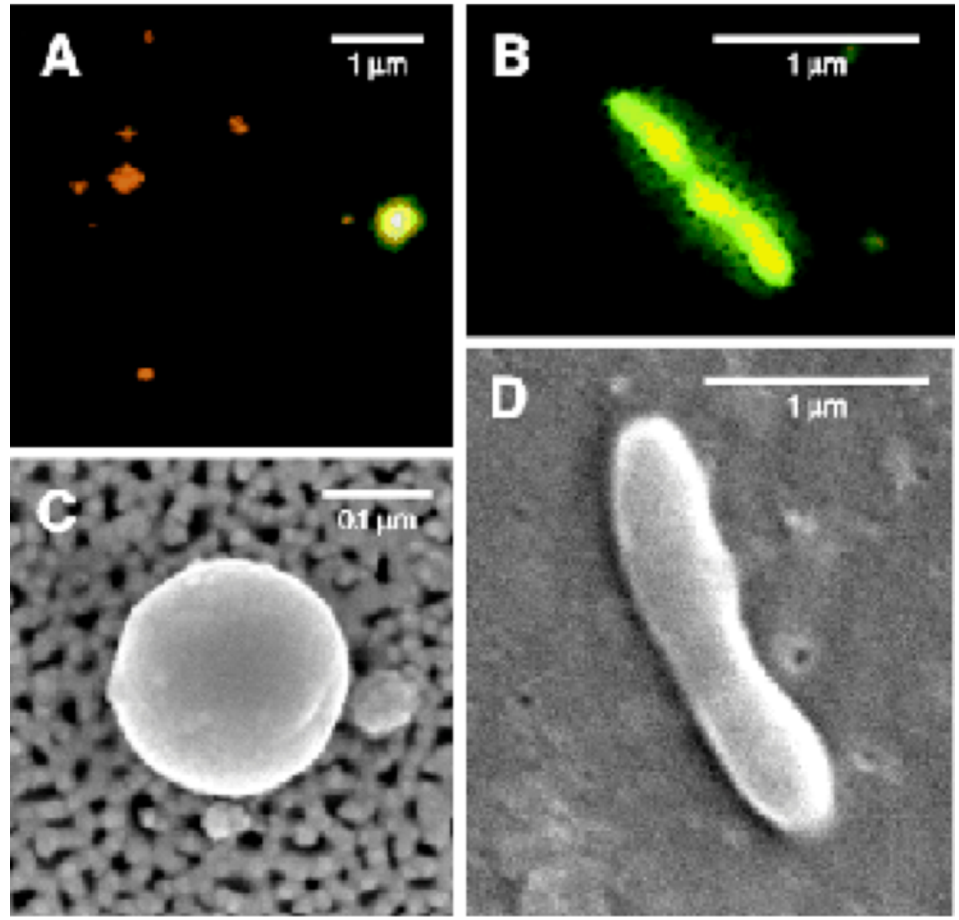
Currently claimed depths	Metabolic status
1.0 km in marine sediment	active
2.8 km in continental rock	?
3.6 km in Antarctic ice	inactive?

Microorganisms in some extraordinary subsurface environments?

Prokaryotes from lake ice 3600 meters below the Antarctic ice surface?

Photomicrographs of prokaryotes from accreted Lake Vostok ice:
(A) a coccoid-shaped cell,
(B) a rod-shaped cell,
(C) an SEM image of a coccoidal cell at a magnification of 1.5 x 105,
(D) an SEM image of the same cell as in (B).

Prokaryotes from this sample respired (but did not grow) in laboratory radiocarbon experiments.

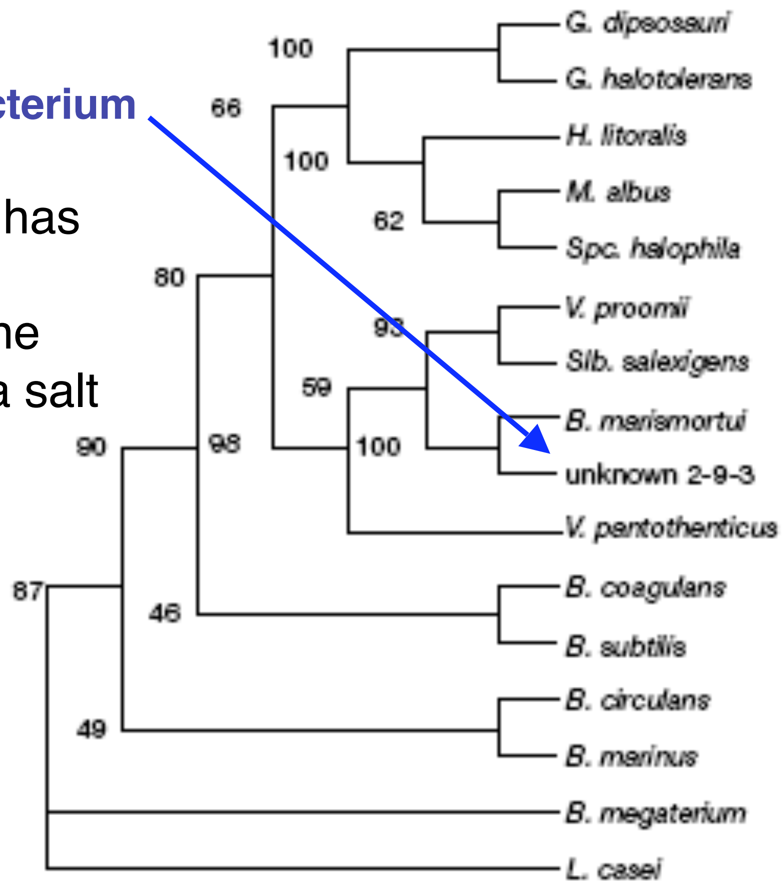


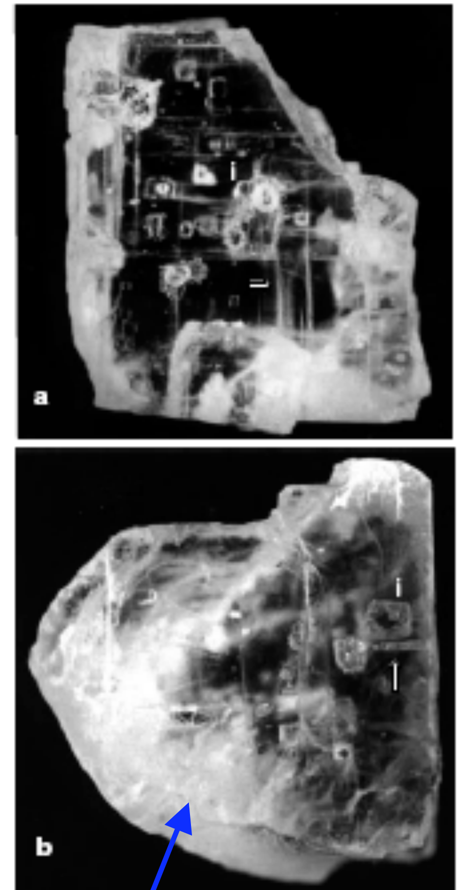
Karl et al. 1999, *Science*.

Organisms in 250 Ma salt?

Isolation and culture has been reported of a bacterium from a brine inclusion in a 250 Ma salt deposit.

Bacterium





Sampled salt piece

Vreeland et al., 2000, *Nature*.

What don't we know?

- *Are these organisms truly indigenous to these extreme environments (ice, amber, salt)?*
- *Are they truly the same age as the matrix that surrounds them?*
- *How do they maintain high enough levels of ATP and RNA to be resuscitated?*
- *How do they survive environmental attack, e.g. by radioactive bombardment?*

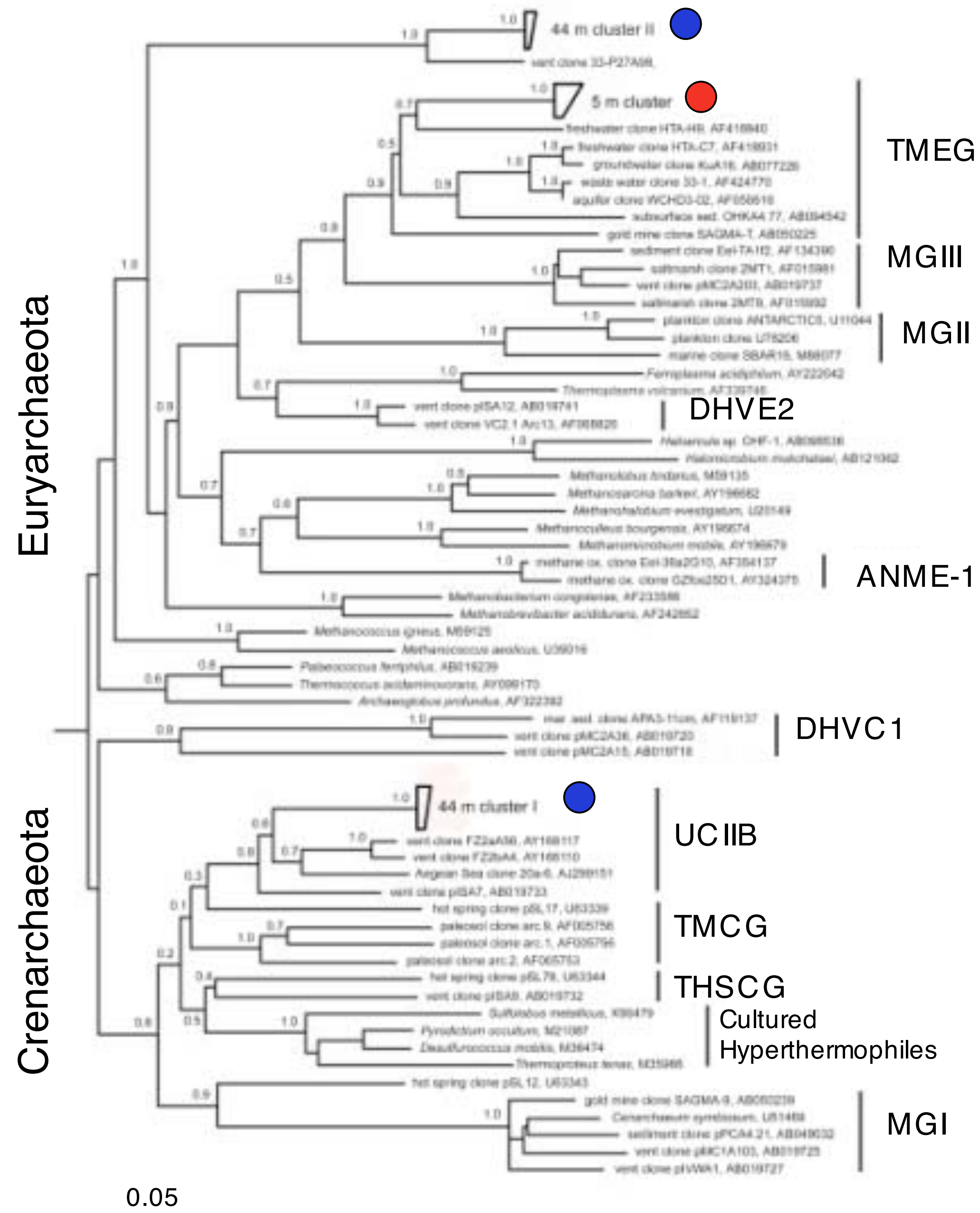
Composition and continuity of deep subsurface communities?

Eastern Pacific Site 1231

5-m cluster

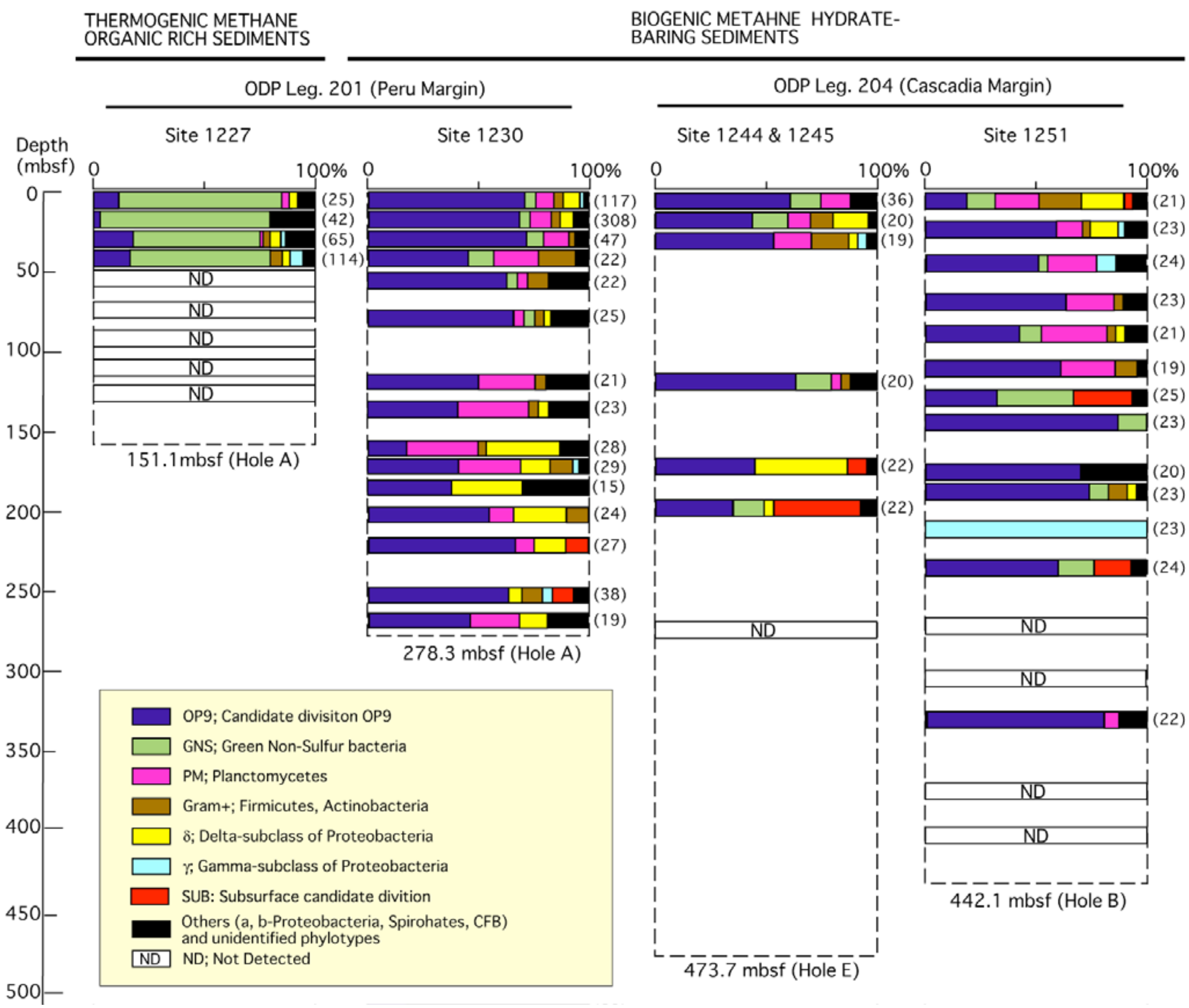
44-m cluster

- Novel prokaryotes are being discovered in subsurface environments (such as these subseafloor sediments).
- Some expected prokaryotes are not being found there.



Data and figure from Sørensen et al., 2004.

Continuity of subsurface communities



Similar subsurface environments separated by 1000s of km have similar communities.

Figure from Inagaki et al., in review.

Summary

- Prokaryotic cells commonly occur in deep subsurface environments.
- Many of these cells are active.
- Novel prokaryotes are being discovered in subsurface environments.
- Communities are genetically similar in similar environments separated by 1000s of km.

Principal sources of energy?

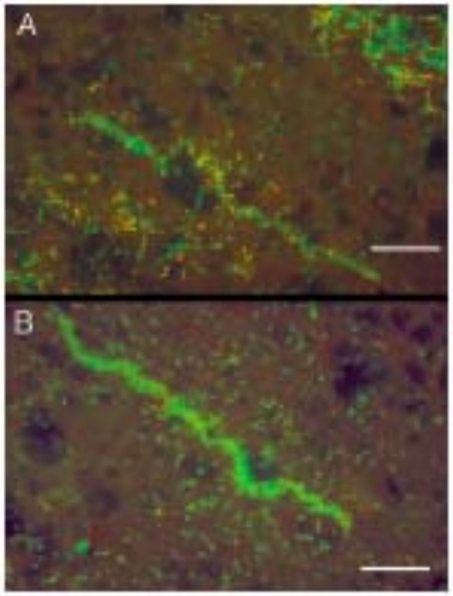
- *What are the principal sources of energy for subsurface life?*
- *To what extent does it depend on the surface world?*

Possible Ultimate Food Sources for Subsurface Life

- Burial of photosynthesized carbon
- Mineral alteration
- Radiolysis of water
- Thermogenesis of reduced molecules

Photosynthesis

The portion of photosynthesized organic matter that gets buried in sediments is a potential food (electron donor) source for subsurface organisms.



Prokaryotes (green) in culture growing on 365 Ma organic shale.

Figure from Petsch et al., *Science* (2001).

Sedimentary life & photosynthesis

Location	Waterdepth	Potential C oxidation by net SO_4^{2-}, Fe(III), Mn(IV) and NO_3^- reduction	Organic carbon burial rate (§)
	(mbsl)	(mol/cm^2-yr)	(mol/cm^2-yr)
Peru Margin Sites			
Shelf Site 1227	427	**$1.8*10^{-6}$**	**$3.1*10^{-6}$**
Slope Site 1230	5086	**$5.0*10^{-6}$**	**$3.1*10^{-6}$**
Open Pacific Sites			
Equatorial Site 1225	3760	**$5.7*10^{-8}$**	**$4.5*10^{-7}$**
Equatorial Site 1226	3297	**$2.8*10^{-7}$**	**$4.6*10^{-7}$**
Peru Basin Site 1231	4813	**$5.0*10^{-9}$**	**$9.4*10^{-7}$**

(§) OC burial rates from Jahnke, 1996.

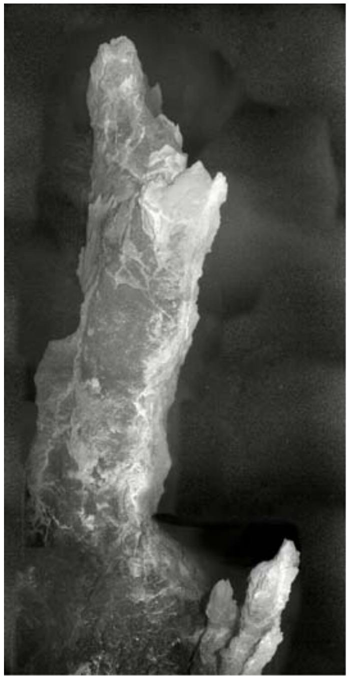
D'Hondt et al., 2004, *Science*.

Mineral alteration

During some processes of mineral alteration, the electron donor H_2 is released

– e.g., during serpentinization of basalt,

$$3Fe(OH)_2 \rightarrow Fe_3O_4 + H_2 + 2H_20.$$



Lost City (Atlantic).

Figure from Kelley et al., *Nature* (2001).

Radiolysis of water

- H_2O is split by protons and alpha particles emitted during radioactive decay.
- All rocks contain radioactive elements (potassium, thorium, uranium).
- Consequently, some radiolysis of water occurs in all wet subsurface environments.
- Products of this radiolysis include electron acceptors (O_2, H_2O_2) and electron donors (H_2, H_3O^-).

Sedimentary life and radiolysis?

Region	Radiolytic H_2 yield in drilled sediment	Total net respiration
	(mols/yr/cm^2-rock)	(mols H_2 equivalents /yr/cm^2-rock)
Peru Margin		
Shelf Site 1227	Not determinable (n.d.)	3.7E-6
Shelf Site 1228	**3.5E-8**	n.d.
Shelf Site 1229	2.6E-8	n.d.
Slope Site 1230	2.9E-8	1.0E-5
Open Pacific		
Equatorial Site 1226	1.1E -8	6.0E-7
Equatorial Site 1225	3.4E-9	1.1E-7
Peru Basin Site 1231	n.d.	**8.0E-8**

Blair, D'Hondt, Spivack, unpublished.

Thermogenesis

From analogy with catalyzed high-temperature industrial reactions, some scientists assume that reduced molecules are created by high-temperature synthesis catalyzed by minerals

- e.g., $CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$, catalyzed by magnetite

Thermogenic creation of CH_4 and other reduced molecules has been hypothesized to support a “deep hot biosphere” (Gold, 1992, *PNAS*).

Exotic ecosystems: are some independent of the surface world?

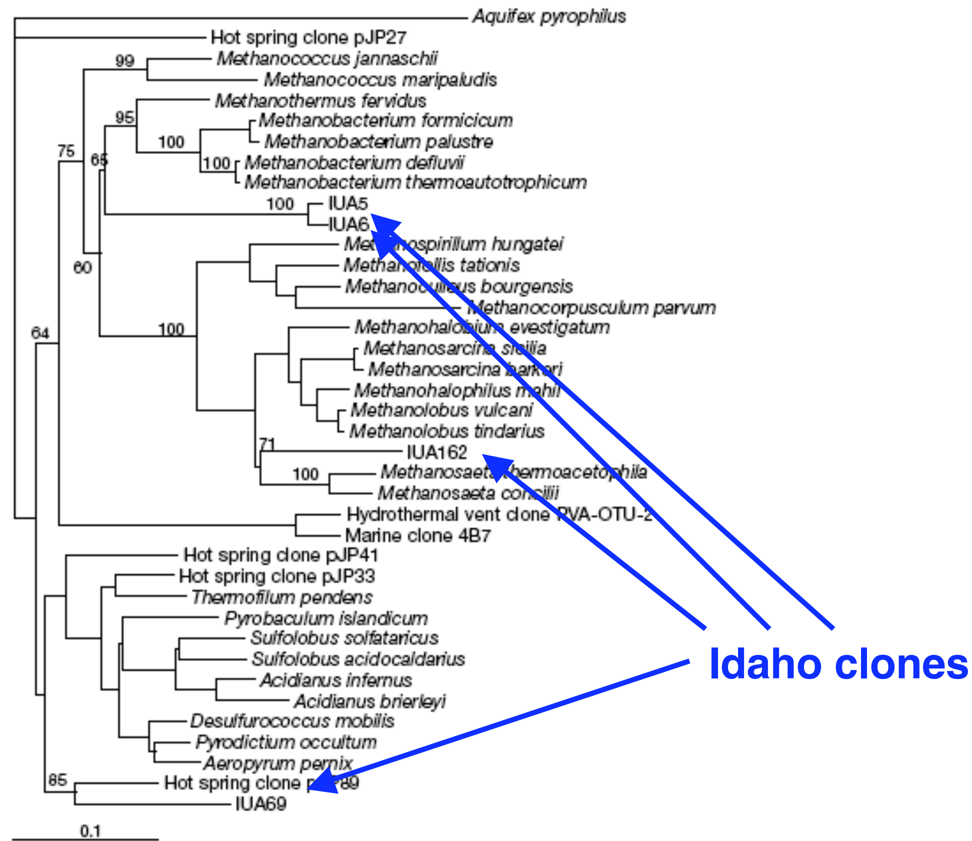
An Idaho hydrothermal system

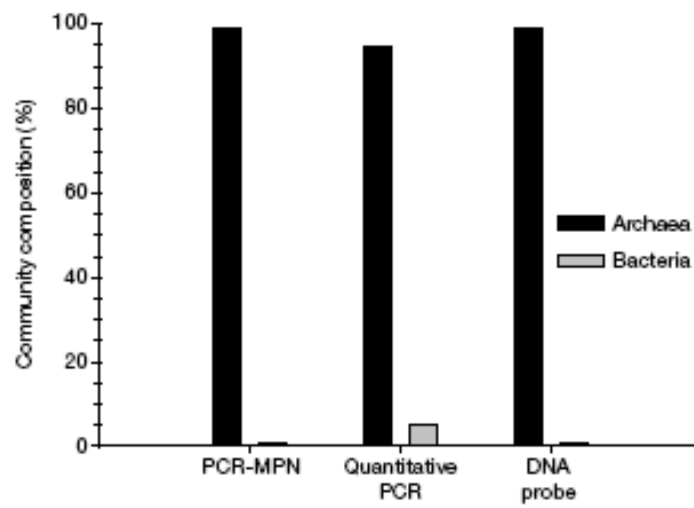
> 90% of the 16S rDNA sequences recovered from a subsurface Idaho hydrothermal system are related to hydrogen-using methanogenic microorganisms.

The authors hypothesize that geothermal hydrogen is the primary energy source for this microbial community:

$4H_2 + CO_2 \longrightarrow CH_4 + 2H_2O$.

If this hypothesis is true, this ecosystem may be independent of photosynthesis.





Chapelle et al. 2002, *Nature*.

Summary

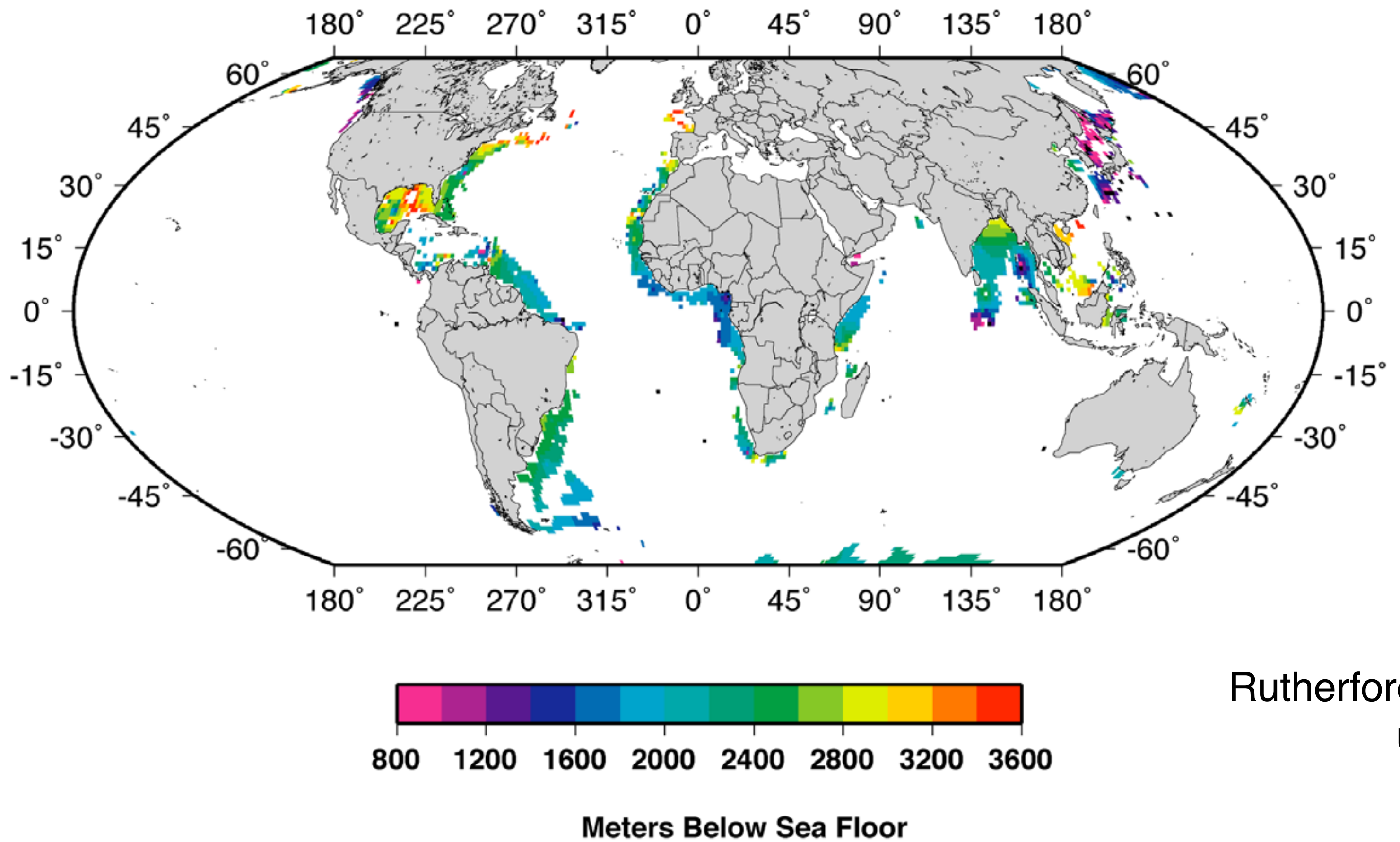
- Most subsurface life may ultimately rely on the surface photosynthetic world for energy.
- Several abiotic processes generate biologically harvestable energy in subsurface environments.
- In principal, some of these processes may sustain life independent of the surface world.

What don't we know?

- *Are there metabolic subsystems in subsurface systems that are ultimately independent of photosynthesis? If so, what are they?*
- *Is life in the Idaho hot spring really independent of photosynthesis? What is its source of hydrogen? What is its source of CO_2?*
- *Does a "deep hot biosphere really exist? If so, what chemical processes sustain it?*

The End.

If the deepest earthly life is temperature-limited…



Rutherford & D'Hondt, unpublished.

Sediment depth below seafloor of 120°C isotherm

Some chemoorganotrophic redox reactions

$$O_2 + CH_2O \longrightarrow CO_2 + H_2O$$

$\Delta G°' = -479$ kJ / mole of organic carbon

$$5CH_2O + 4NO_3^- \longrightarrow 2N_2 + 4HCO_3^- + CO_2 + 3H_2O$$

$\Delta G°' = -453$ kJ / mole of organic carbon

$$CH_2O + 3CO_2 + H_2O + 2MnO_2 \longrightarrow 2Mn^{2+} + 4HCO_3^-$$

$\Delta G°' = -349$ kJ / mole of organic carbon

$$CH_2O + 7CO_2 + 4Fe(OH)_3 \longrightarrow 4Fe^{2+} + 8HCO_3^- + 3H_2O$$

$\Delta G°' = -114$ kJ / mole of organic carbon

$$2CH_2O + SO_4^{2-} \longrightarrow H_2S + 2HCO_3^-$$

$\Delta G°' = -77$ kJ / mole of organic carbon

Some chemolithotrophic reactions

$H_2 + 1/2O_2 \longrightarrow H_2O$

$\Delta G°' = -237$ kJ / reaction

$5NH_4^+ + 3NO_3^- \longrightarrow 4N_2 + 9H_2O + 2H^+$

$\Delta G°' = -1483$ kJ / reaction

$3S^0 + 2FeOOH \longrightarrow SO_4^{2-} + 2FeS + 2H^+$

$\Delta G = \sim -90$ kJ / reaction in culture conditions (K. Finster, www, 6/04)

$S^0 + 3MnO_2 + 2H_2O \longrightarrow SO_4^{2-} + 3Mn^{2+} + 4OH^-$

$\Delta G = \sim -90$ kJ / reaction in culture conditions (K. Finster, www, 6/04))