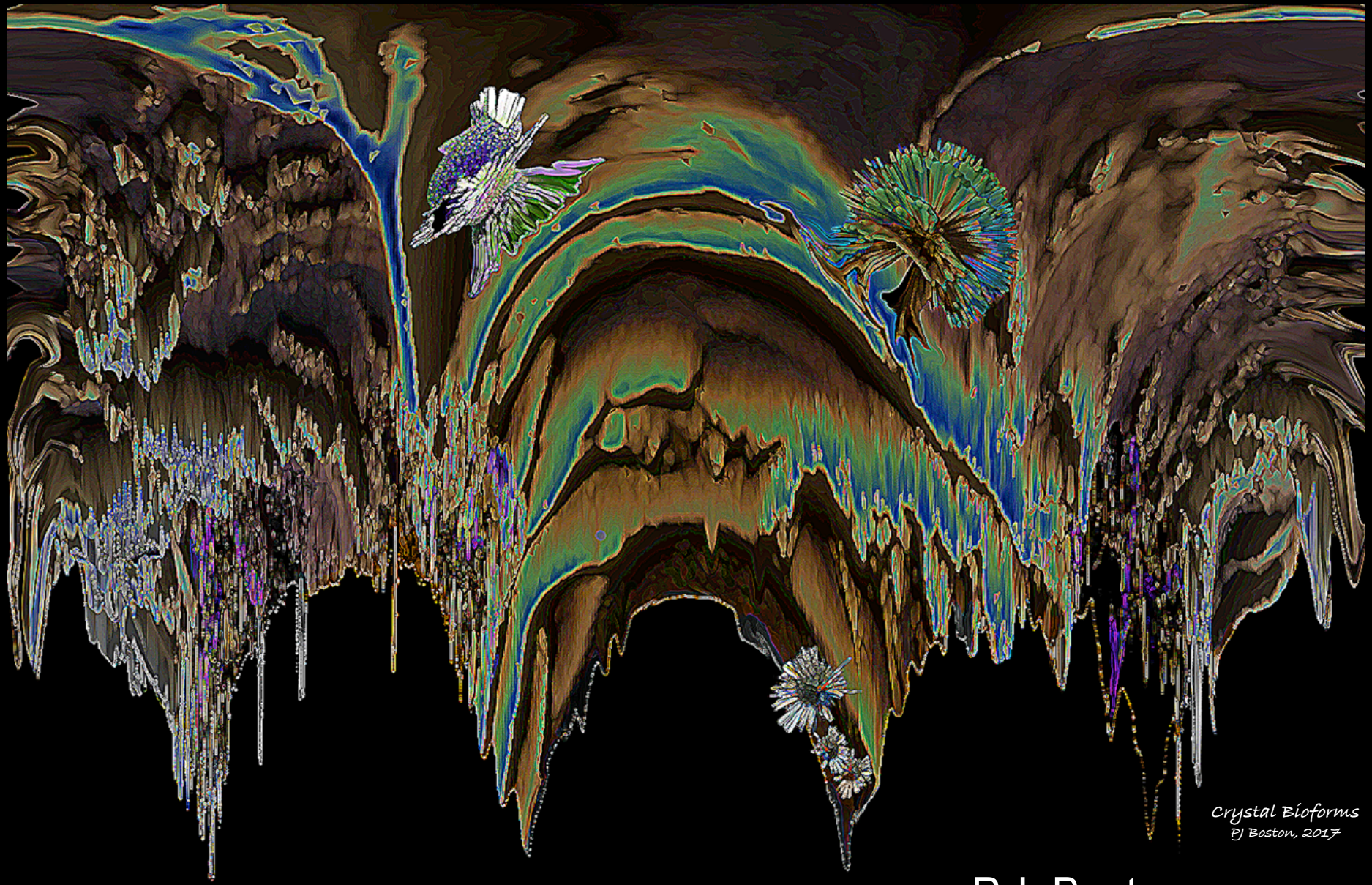


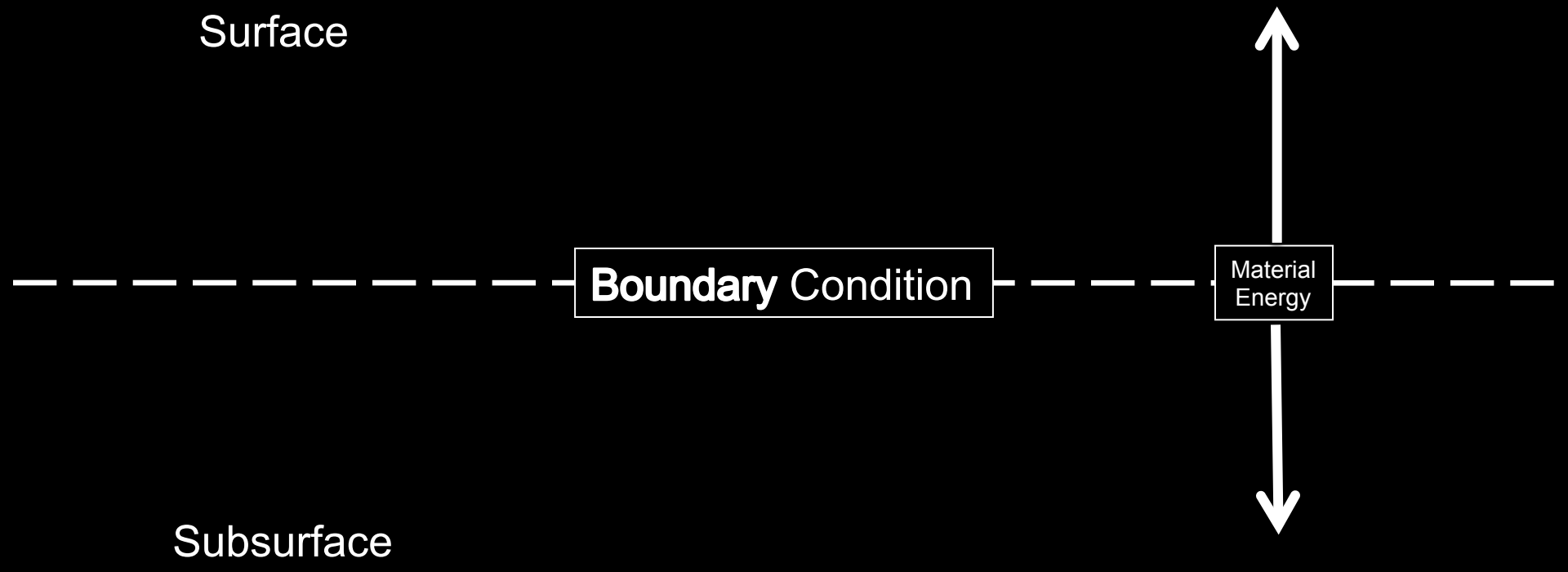
Cave Life Overview

P.J. Boston

Director, NASA Astrobiology Institute
NASA Ames Research Center
Moffett Field, CA

What is a Cave?

(physics version)



Caves in Many Rock Types

Four Windows Lavatube,
El Malpais Nat. Monument. Grants, NM
Image by Kenneth Ingham

Granite spalling caves
Gallicia, Spain

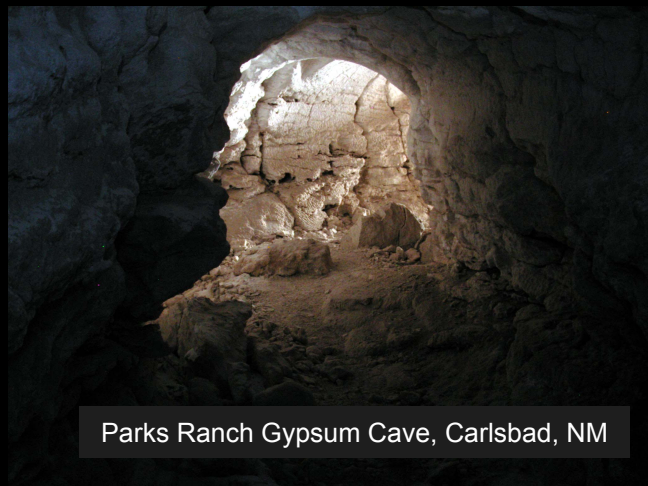
Lechuguilla Cave, Carlsbad, NM
created by sulfuric acid and limestone
Image by Dave Bunnell

Cueva de Charles Brewer
Quartzite Cave, Venezuela
Image by Charles Brewer

Antarctic ice caves, Mt. Erebus
Image courtesy of Aaron Curtis

Caves in Halite (salt)
Atacama Desert, Chile

Lilburn Marble Cave, CA
Image public domain



Parks Ranch Gypsum Cave, Carlsbad, NM

Process-based Cave Classification of Target Bodies-2015

CAVE TYPE	Dominant Processes	Parent Materials	Earth Examples	WHERE????
Solutional	Dissolving rock by solvent *(With or without chemistry)*	Soluble solids plus a solvent	Classic karst, gypsum, halite	Earth, Titan, Mars
Erosional	Mechanical abrasion via wind, water, grinding, crystal wedging, etc.	Any solid	Sea coast caves, Tafonation, Aeolian rock shelters, etc.	Earth Mars (aeolian, tafonation) Titan (coastal?) Venus (aeolian?)
Tectonic	Fracturing due to internally or externally caused earth movements	Any rocky solid (internal tectonism and external impacts)	Seismic caves	Earth, Europa Ganymede? Titan, Enceladus Mars
Suffosional	Cavity construction by the fluid-borne motion of small particles	Unconsolidated sediments	Mud caves, some thermokarst	Earth Mars (poles, RSL layers?)
Phase Transition	Cavity construction by melting, vaporization, or sublimation	Meltable or sublimable materials capable of solidifying at planet-normal temperatures	Lava tube caves, glacial caves (i.e. caves in ice as bedrock)	Volcanic bodies (Earth, Mars, Venus, Io) Comets
Constructional	Negative space left by incremental biological or accretional processes, often around an erodable template	Any solid capable of ordered or non-ordered accretion, or biogenic processing	Coralline algae towers, travertine spring mound caves	Earth Mars (spring mound cavities)
Compound Mechanisms *	Catastrophic speleogenesis	Rocky soluble solids	Flynn Creek Impact	Earth, Mars

Ceres?
Vesta?
Pluto?
Mercury?
Uranus' moons?

Modified EVEN MORE from P.J. Boston 2004. Extraterrestrial Caves. In, *Encyclopedia of Caves and Karst, J. Gunn, ed.*

* Boston et al. 2006. **In,** *Karst Geomorphology, Hydrology, & Geochemistry* GSA Special Paper 404. Pp. 331-344.

** Milam et al. 2005. Flynn Creek Impact Structure. 69th Ann. Meteoritical Soc. Meeting Field Guide.

What Kind of Planet Is It?

Planet Type 1 Biosphere

Sunlight "just right"
Green
Gooey
Gases in non-equilibrium

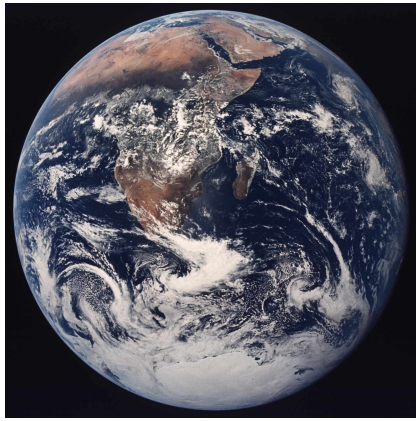
Critical Zone is top-down
Photosynthetically driven

Planet Type 2 Biosphere

No visible means of support
Not green
Not gooey
Gases in chemical equilibrium
Exceptions dependent upon crustal leakiness

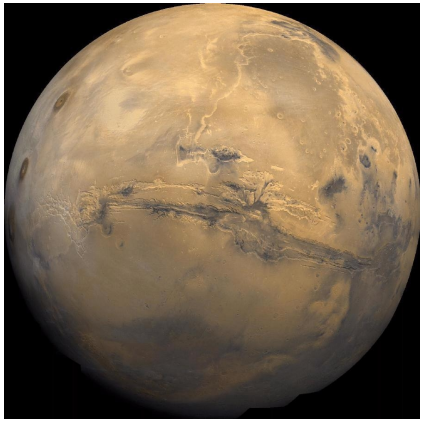
Critical Zone is bottom-up
Chemosynthetically driven

Well mixed-Critical Zone

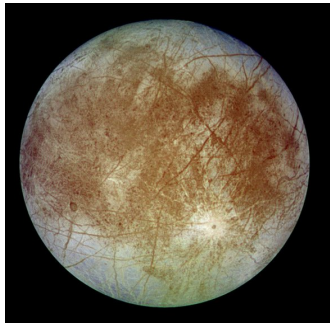


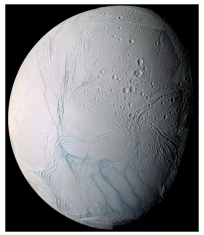
Earth

Stratified Critical Zone?



Mars





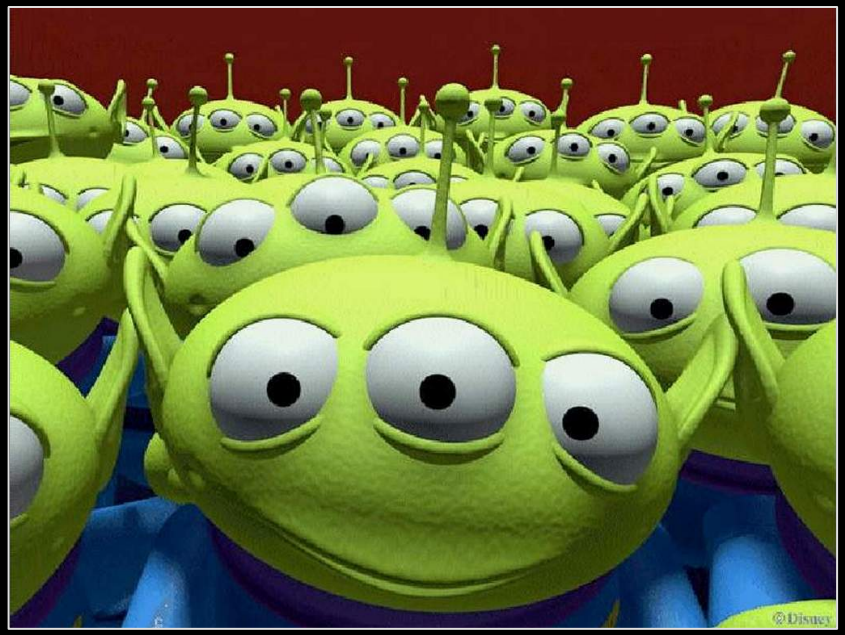
Europa & Enceladus

Boston et al 2011, 2012

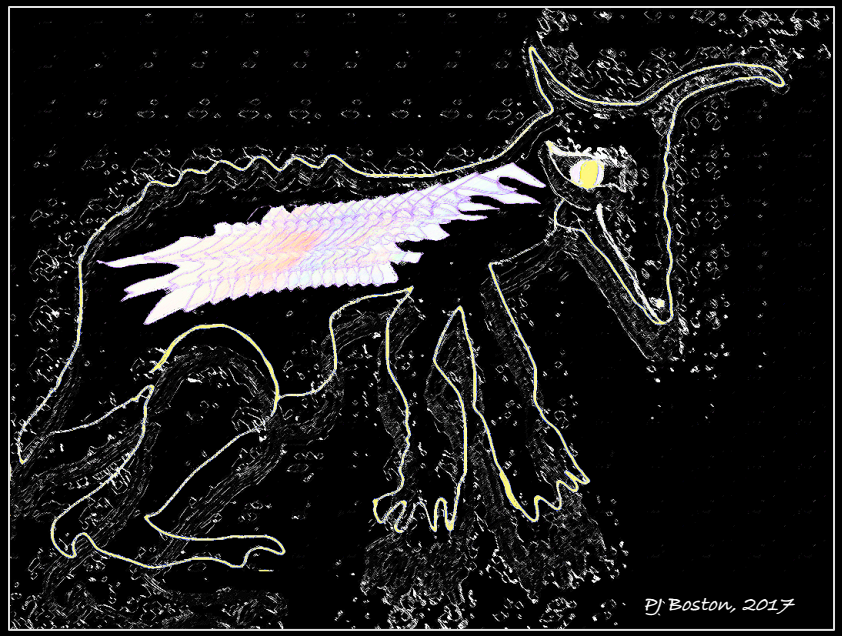
What Kind of Life Are We Looking For?

Both!

Alive….Extant Life



No Longer Alive….Extinct Life



Fossil Dinosaur Proud of Her Backbone

Biosignature Life-O-Meter

Extant Life

✧ Life-produced Gases
- Oxygen
- Methane
- Ammonia
- Complex atmospheric spectrum

✧ Biological Molecules
- Live organisms!!!
- Chlorophyll on Earth
- Other photosynthetic pigments?
- "Sufficiently complex" organics….
- Molecular fossils

✧ Morphological Fossils
- True fossils (body fossils!)
- Biominerals
- Biotextures
- Biopatterns

Extinct Life

✧ Geochemical Traces
- Isotopic fractionation
- Life chemistry alteration of rock record
- Life chemical traces trapped in geological materials

Guardian by Joel Hagen
courtesy of the artist

Subsurface “Macroporosity” (aka Caves) Preservation Modes

- No surface weather
- Often little or no mechanical disturbance for a long time
- Splendid preservation environment!

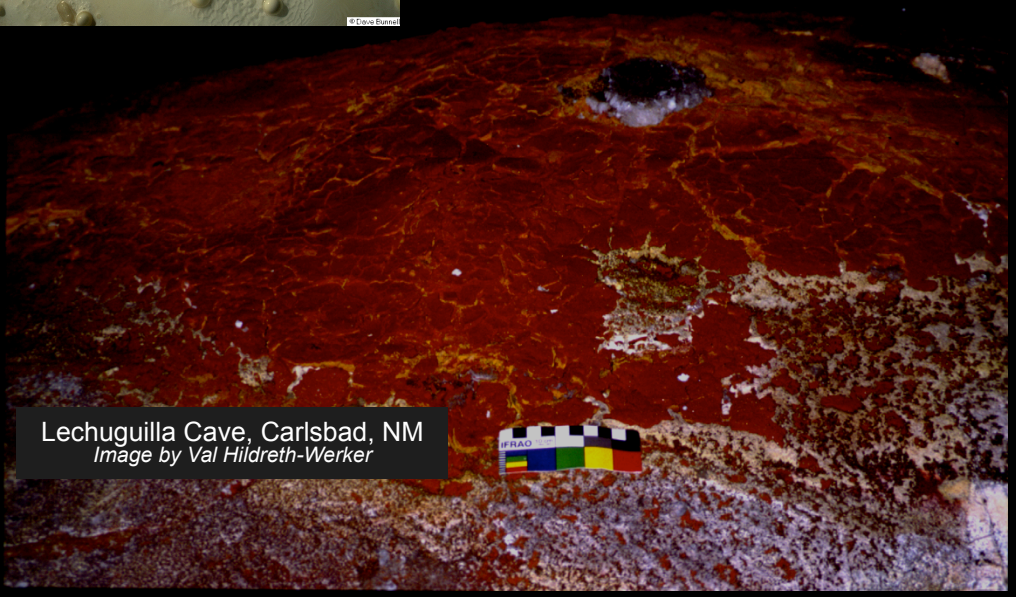
- Entombment by minerals (active metabolism or passive attraction)
- Entombment in minerals (including in fluid/gas inclusions)

- Microbial communities often self-fossilizing!
- No burial diagenesis necessary!
- Results from metabolic byproduct accumulation
- Metals, non-metals

- Subsequent infill and/or collapse provides “sealant” later
    - *(On Earth, oldest known is Jenolen Caves, 250mya)*

Unparallelled Preservation Environments

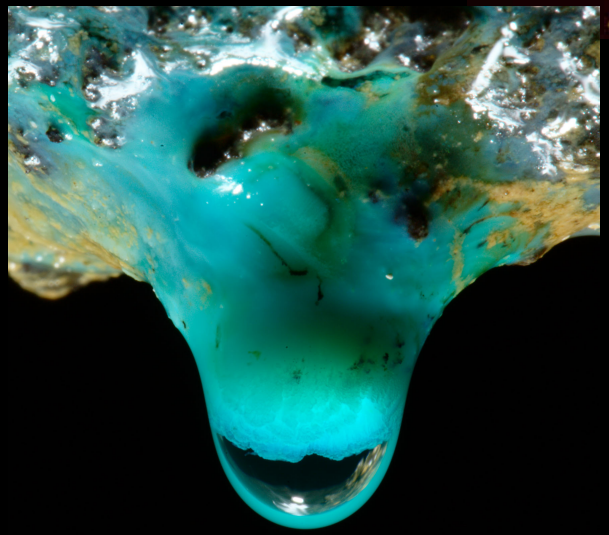
Minerals, Biominerals, Biotextures, Mummies…



Lechuguilla Cave, Carlsbad, NM
Image by Val Hildreth-Werker

Human infant, Antofagasta, Chile, ~3kya

Snowy River, Ft. Stanton Cave, NM
Courtesy of K. Ingham



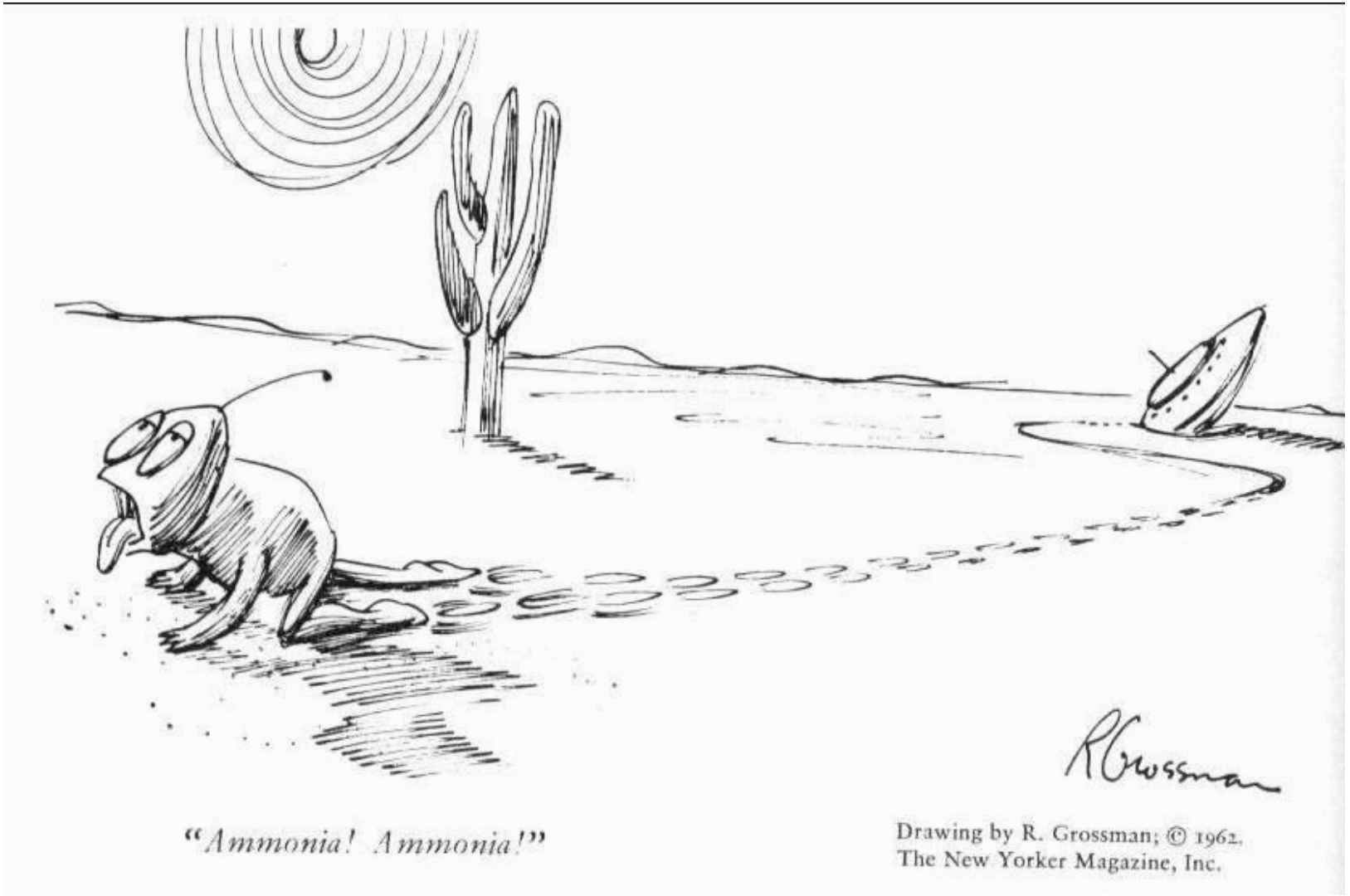
Copper speleothem, Hawaii
Courtesy of K. Ingham

“Fossilization Front” observed in biomats transitioning to calcite/sulfate

Lithification front, Cueva de Villa Luz, Mexico
Image courtesy of K. Ingham

Ridiculously Hard Task #1:

Figuring out possible lifeforms from first principles!

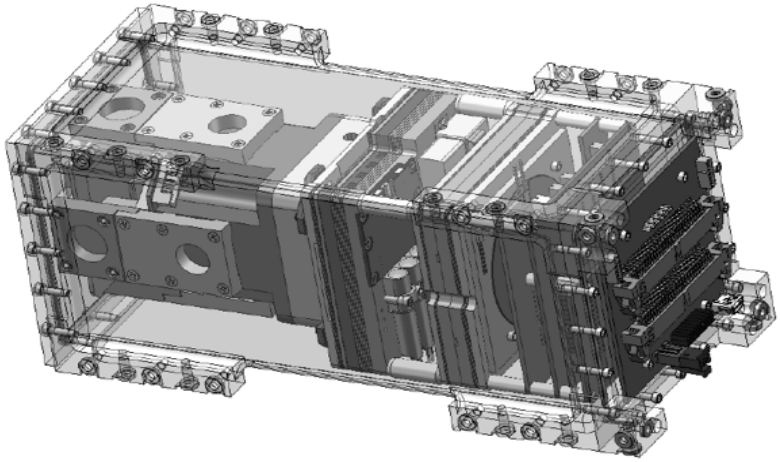


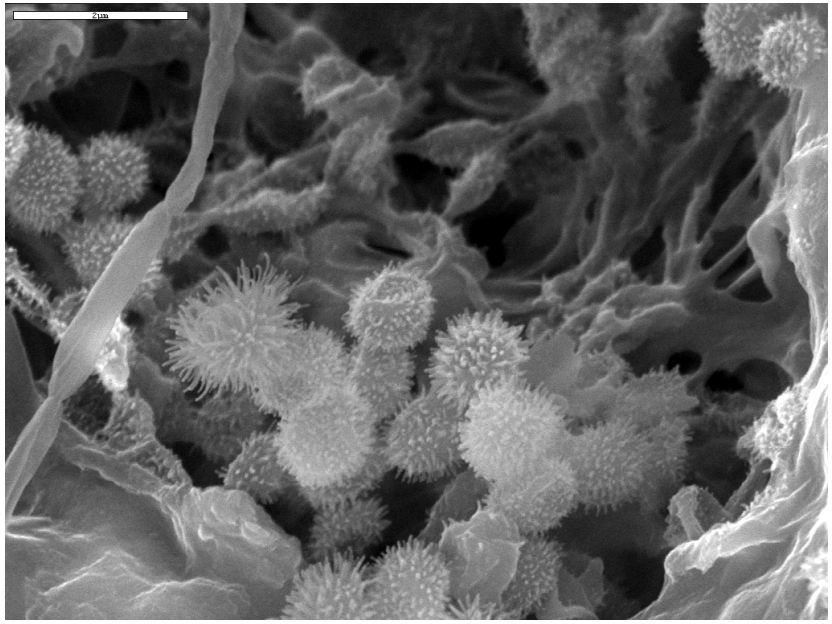
The Subsurface Microbe's Existential Crisis

Answer A: Evolutionary "losers" who have retreated to the subsurface because they simply can't compete for delicious surface organics?

Answer B: Subterranean microbial biosphere that has persisted over much of Earth's history & may even have originated there?

What we are currently mostly doing…
Life Detection by circumstantial evidence....



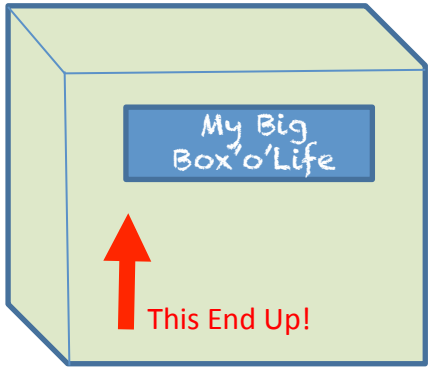


Micro-chrysanthemum Garden, Un-named lavatube, Canary Islands
By M.N. Spilde & P. Boston

- ✓ Suspiciously complicated organic compounds
- ✓ Co-location of possibly biological compounds
- ✓ Patterns of molecular occurrence

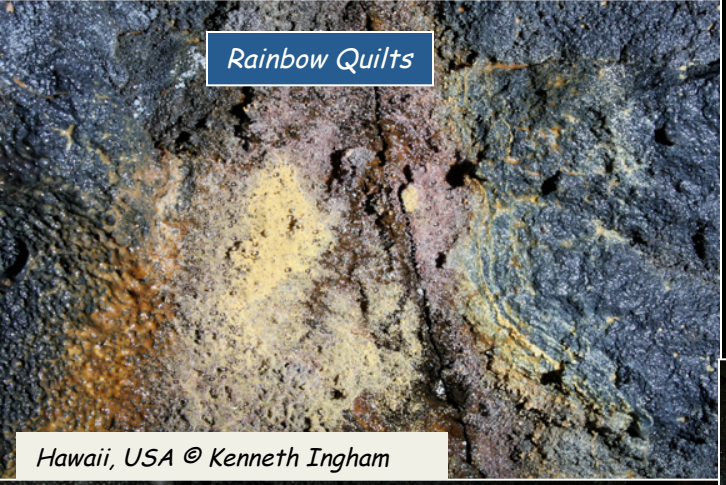
- ✓ Suspiciously complicated structure
- ✓ Co-location of numerous units
- ✓ Patterns in structures (macro & micro)

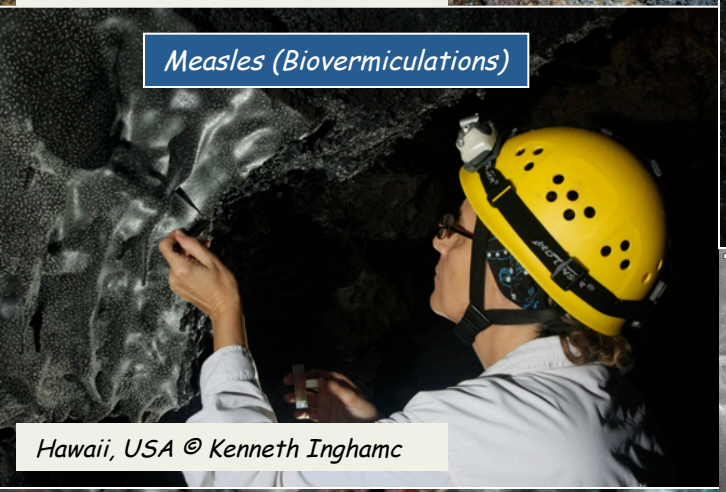
Life is NOT a bulk property!

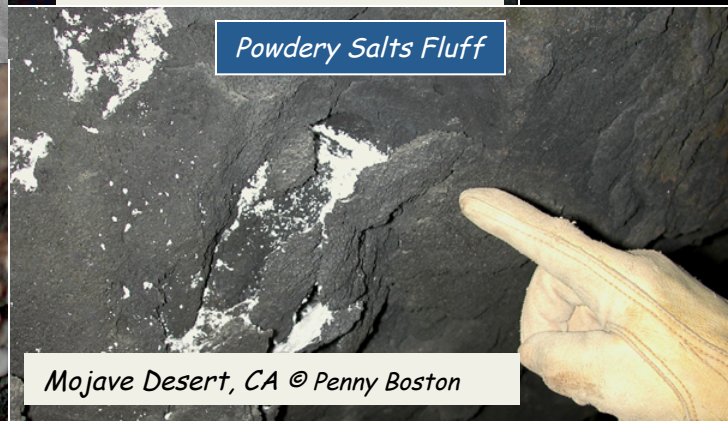


Oh no, it's not….

Dramatis Personae





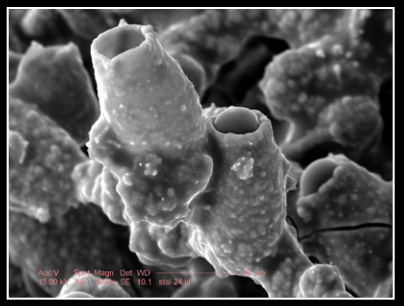


Biosignature Suites at Many Scales

The Hunt for Blue Goo
Copper Subsurface Organisms

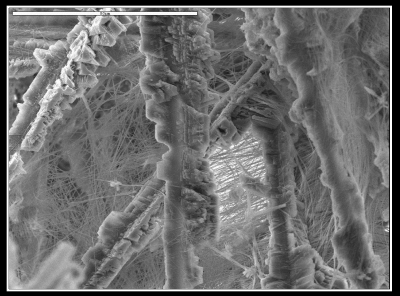
snottites!
Image courtesy K. Ingham

Red Tulip Microbial Iron Stalagmites, Zoloushka Cave, Ukraine



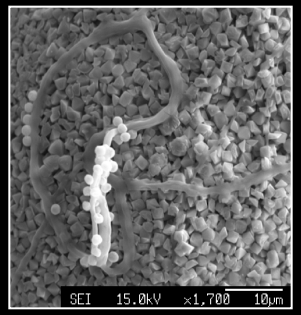
Red Tulip Microbial Iron Stalagmites, Zoloushka Cave, Ukraine

Poofball Sea, Thrush Cave, SE Alaska

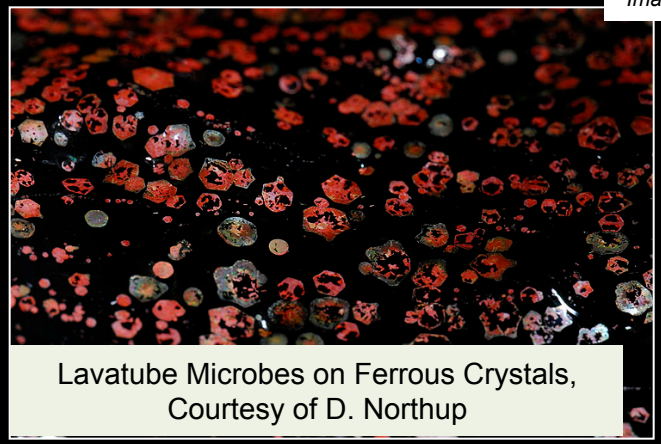


Phlegm ball mats
Image courtesy K. Ingham

Poofball Sea, Thrush Cave, SE Alaska



SEMs by M. Spilde & P. Boston



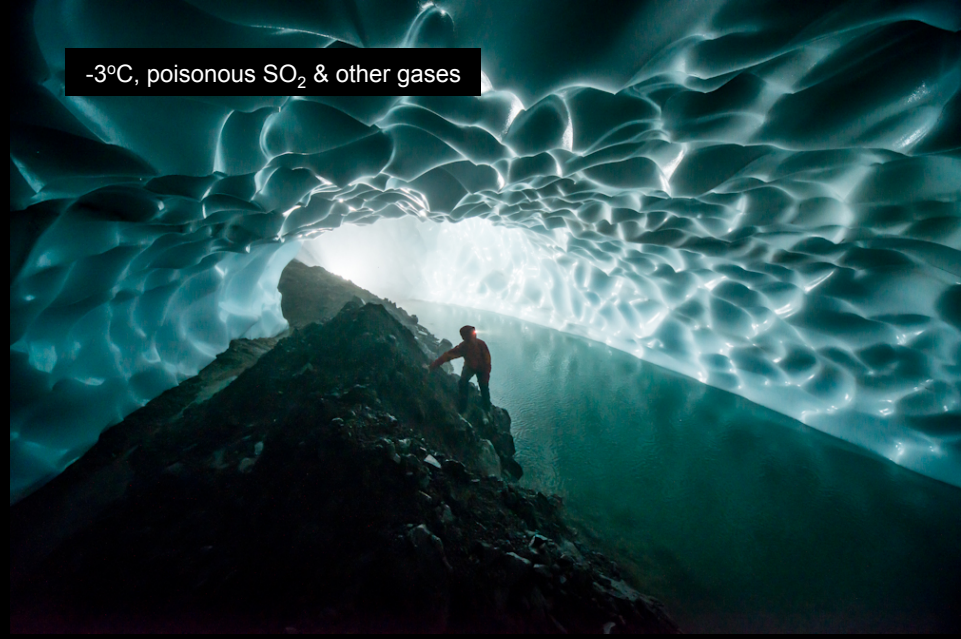
Lavatube Microbes on Ferrous Crystals, Courtesy of D. Northup

Manganese Microbe Stalagmite on Miner's Jacket, Soudan Mine, MN

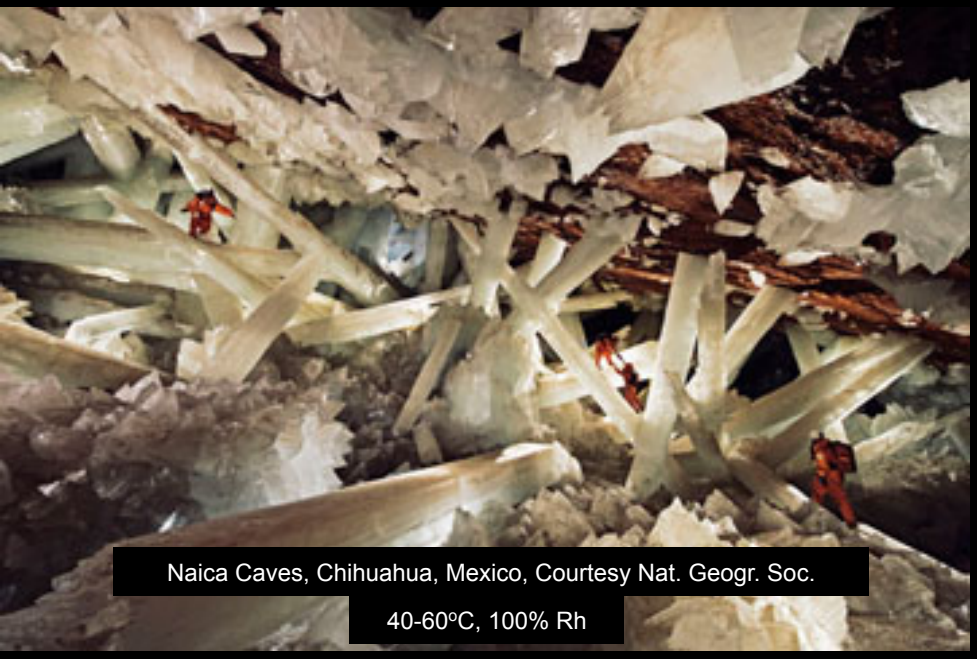
Boston, P.J. et al 2001. Cave biosignature suites: Microbes, minerals and Mars. *Astrobiology* 1(1):25-55.

Cueva de Villa Luz, Tabasco, Mexico, Courtesy Nat. Geogr. Soc.

Sulfuric acid (pH=0), H_2 S, CO, & other poisonous gases



Fumarolic Ice Caves, Mt. Rainier, WA, Courtesy Eddy Cartaya



Unifying Themes

- Significant similarities in ecosystem properties between different systems

- Ubiquity of metal oxidation for energy
- Ubiquity of biofilms & mats

- Functionally indivisible obligate multi-species communities
- Microbial pioneer species invade bedrock

- VERY slow growth rates
- Very small cell sizes
  (100 - 500 nm diam. common)

- Unusual preponderance of weird shapes
- Stupefyingly large biodiversity as we currently count it

- Mineral reprecipitation by (& on) organisms
- *In situ* self-fossilization

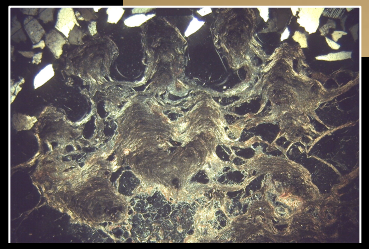
Between different subsurface chemistries & communities:

Boston, et al. 2009. *Hypogene Speleogenesis and Karst Hydrology of Artesian Basins. Special Paper 1*:51-57. *Ukr Inst. Karstol. Speleol. Simferopol, UK*

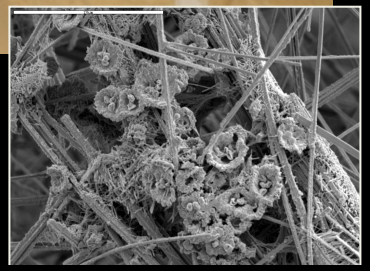
Carbonate Biofilms

Calcite moonmilk, Crisco Passage, Spider Cave, NM

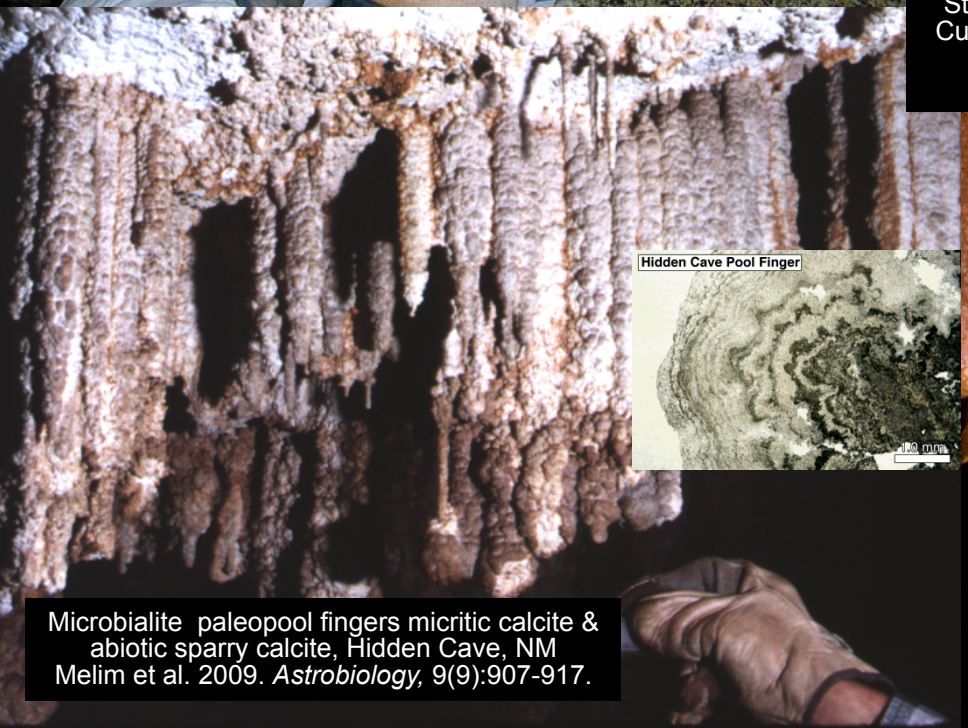
Live pool fingers, Germany.



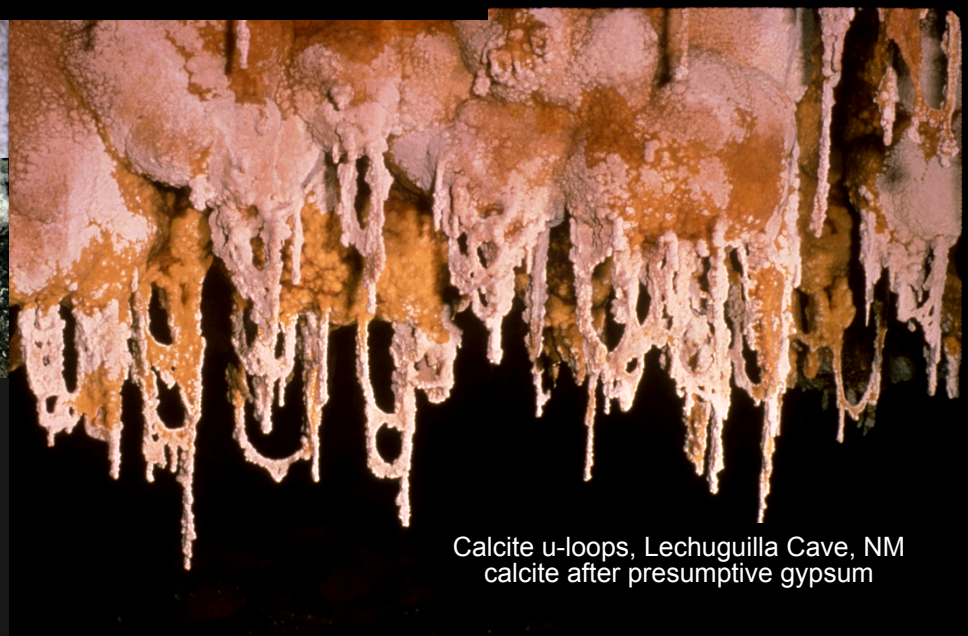
Stromatolite-like structure in moonmilk. Curry et al 2009. *International Journal of Speleology* 38(2):111-128.



"Birds nests" in live moonmilk

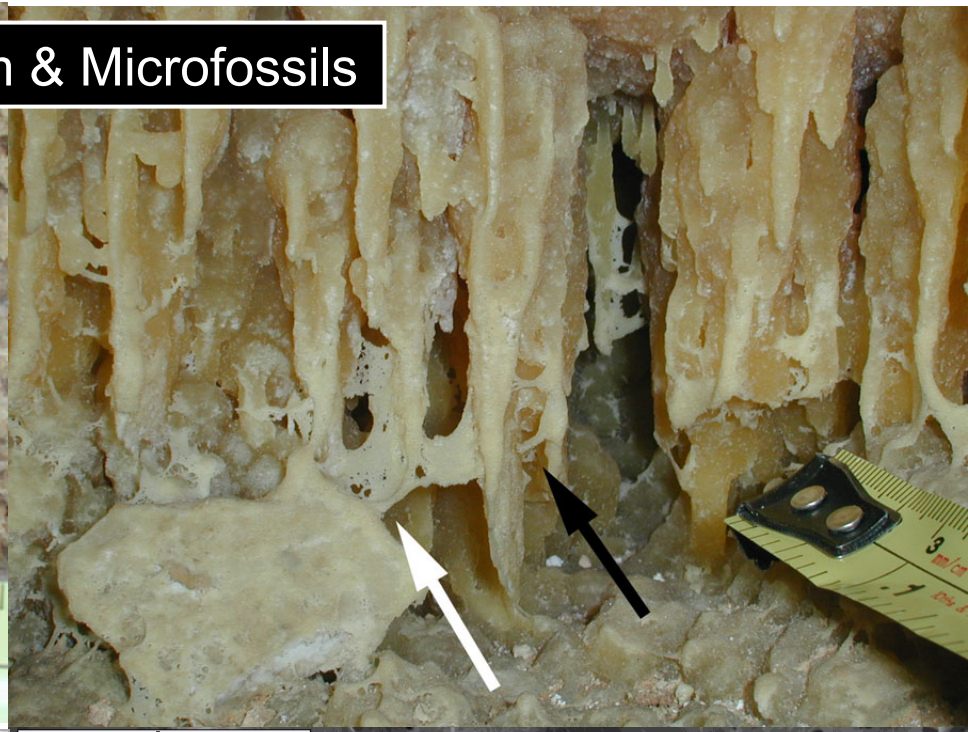


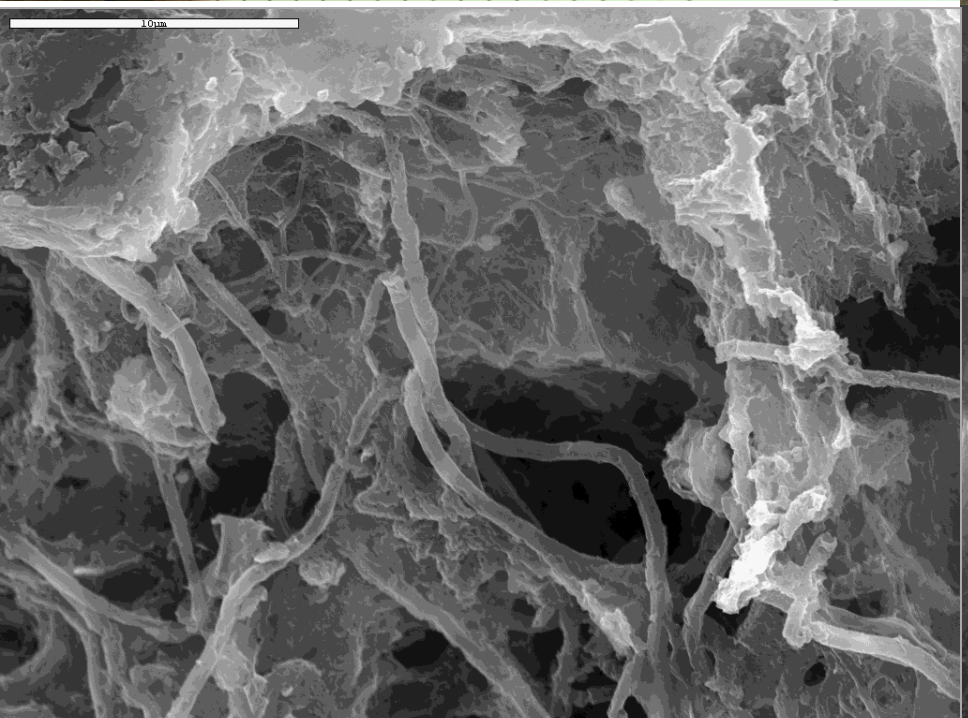
Microbialite paleopool fingers micritic calcite & abiotic sparry calcite, Hidden Cave, NM
Melim et al. 2009. *Astrobiology,* 9(9):907-917.

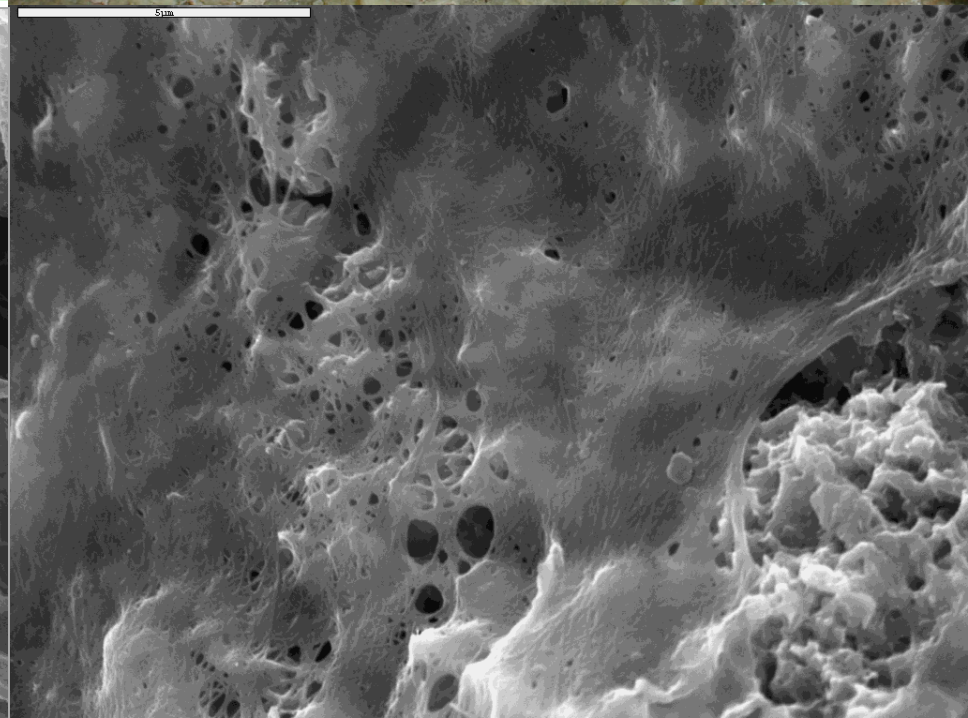


Calcite u-loops, Lechuguilla Cave, NM
calcite after presumptive gypsum

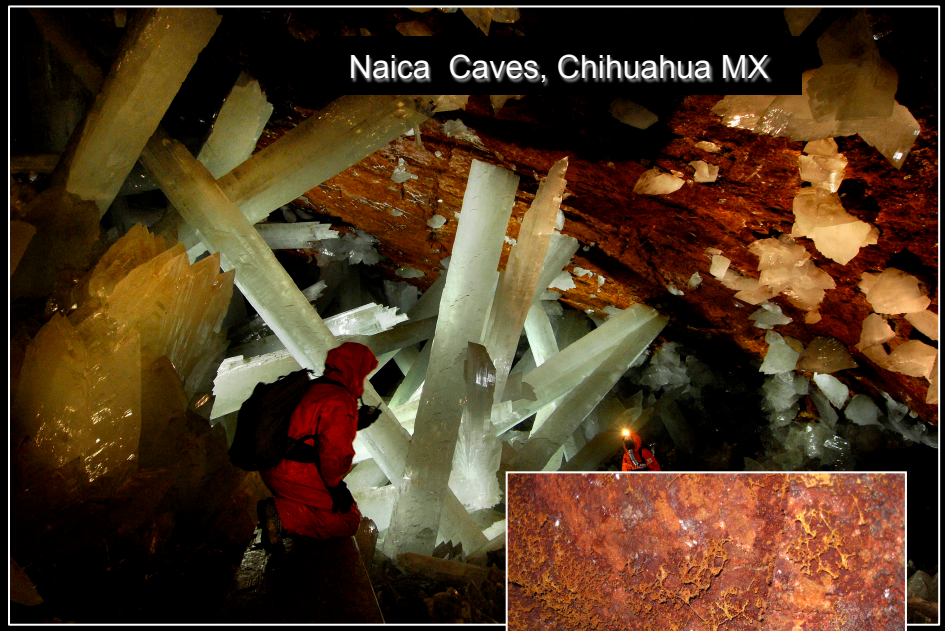
Lithified Biofilm & Microfossils

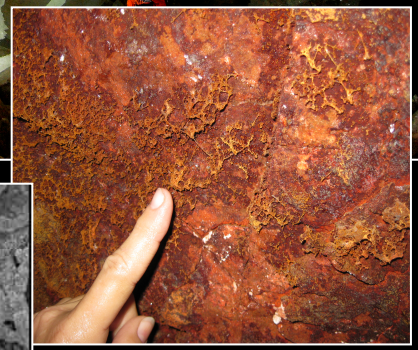


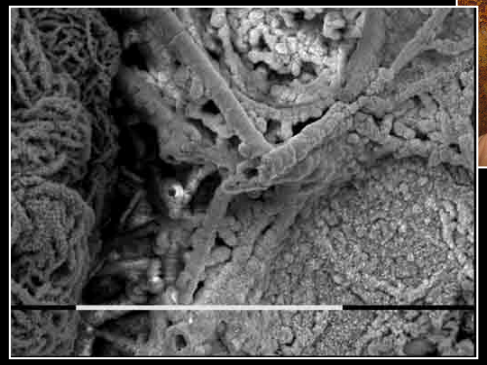


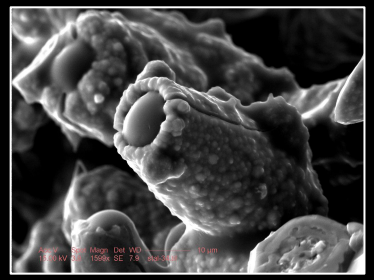


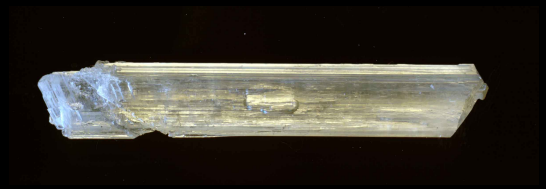
Iron & Manganese Auto-Fossilization

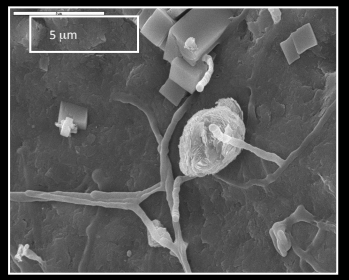




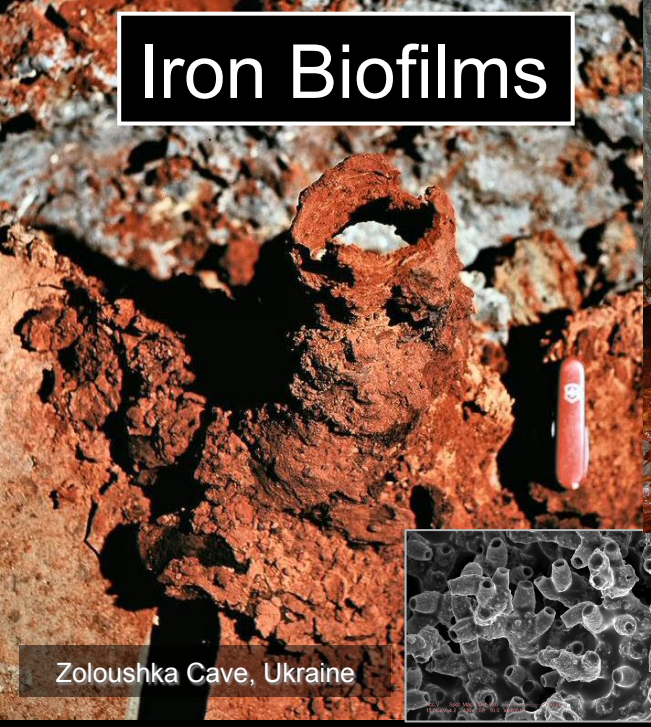






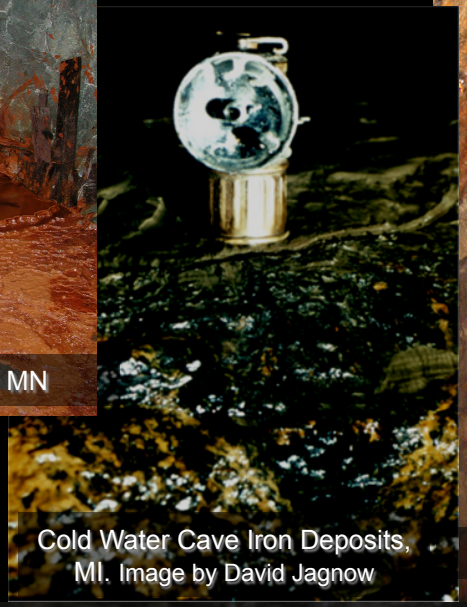


Iron Biofilms



Zoloushka Cave, Ukraine

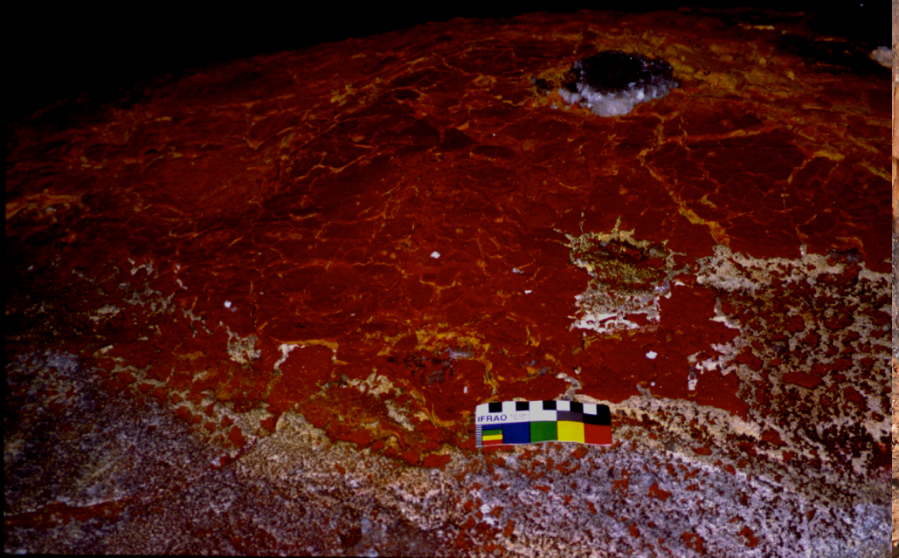
Soudan Iron Mine, MN



Cold Water Cave Iron Deposits, MI. Image by David Jagnow

Zu Azufriel, Sardinia, Italy

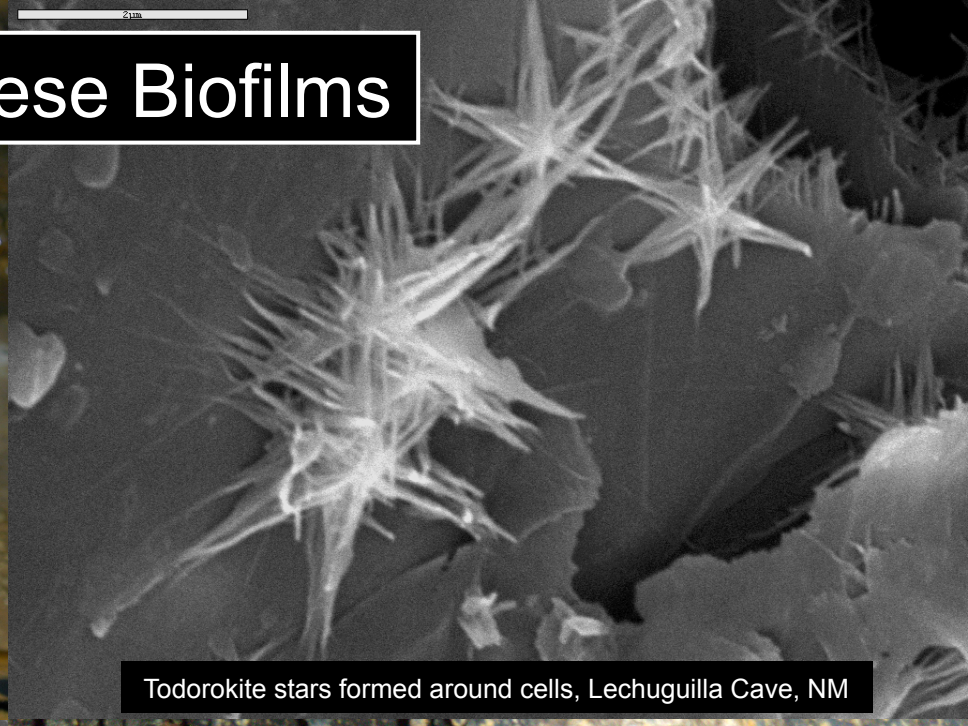
Picasso Rock, Lechuguilla Cave, NM
Image by Val Hildreth-Werker



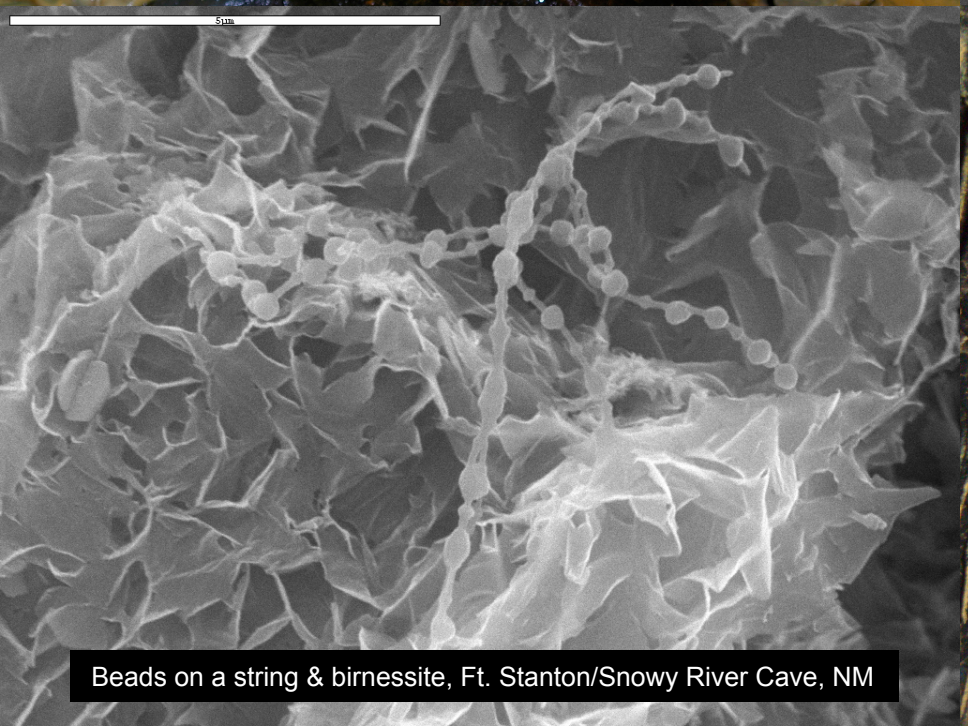
Pool fingers, Carlsbad Cavern, NM. Photo by Peter Bosted

Manganese Biofilms

Manganese microbialite on abandoned miner's jacket, Soudan Mine, MN



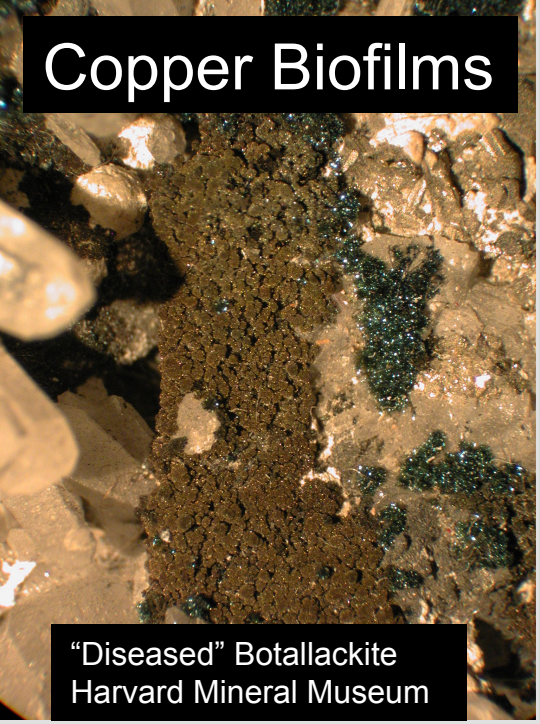
Todorokite stars formed around cells, Lechuguilla Cave, NM



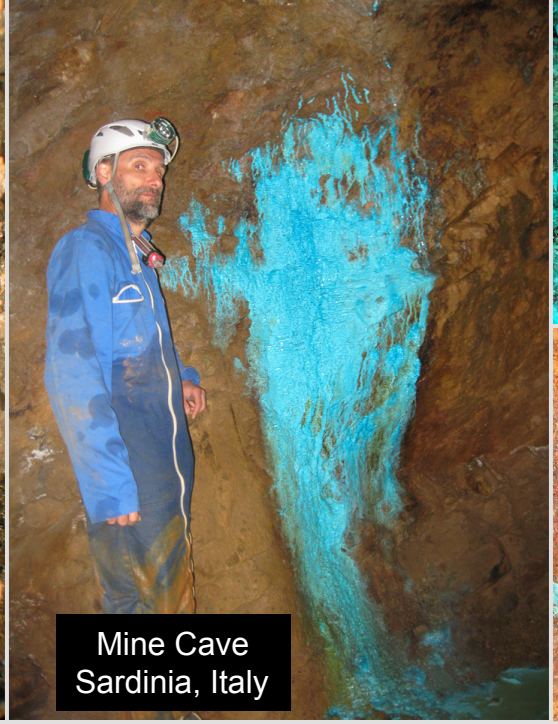
Beads on a string & birnessite, Ft. Stanton/Snowy River Cave, NM

Mud manganese snottites, Zoloushka Cave, Ukraine

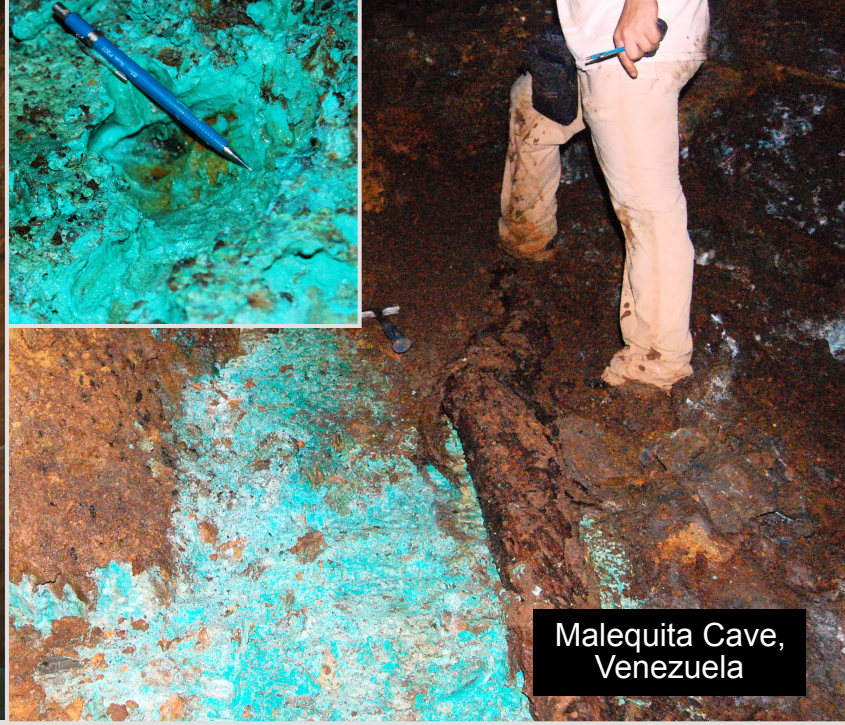
Copper Biofilms



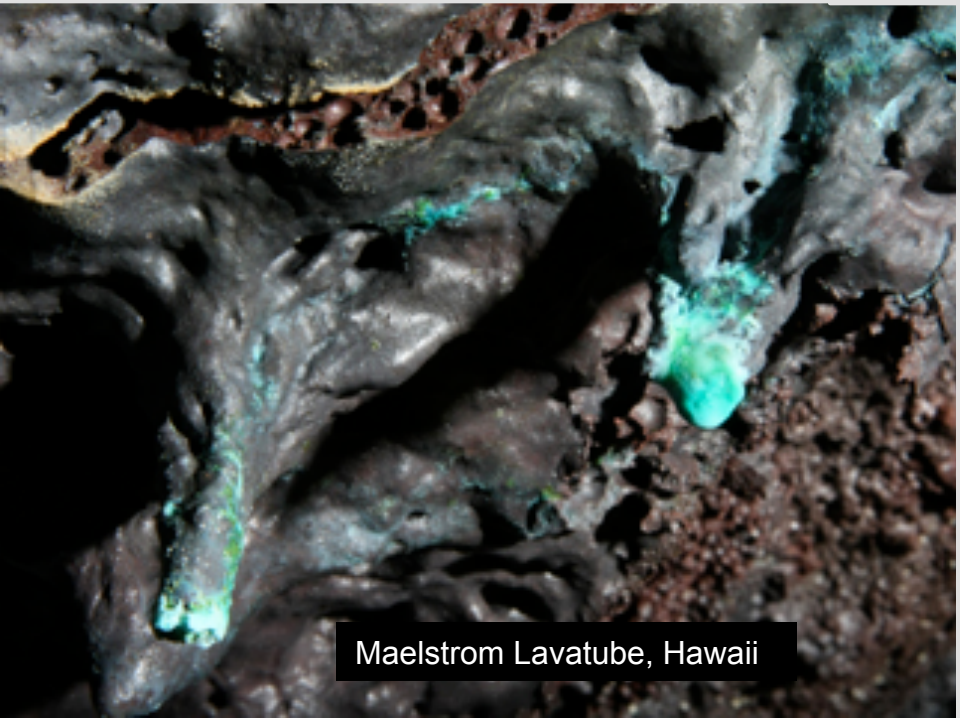
"Diseased" Botallackite
Harvard Mineral Museum



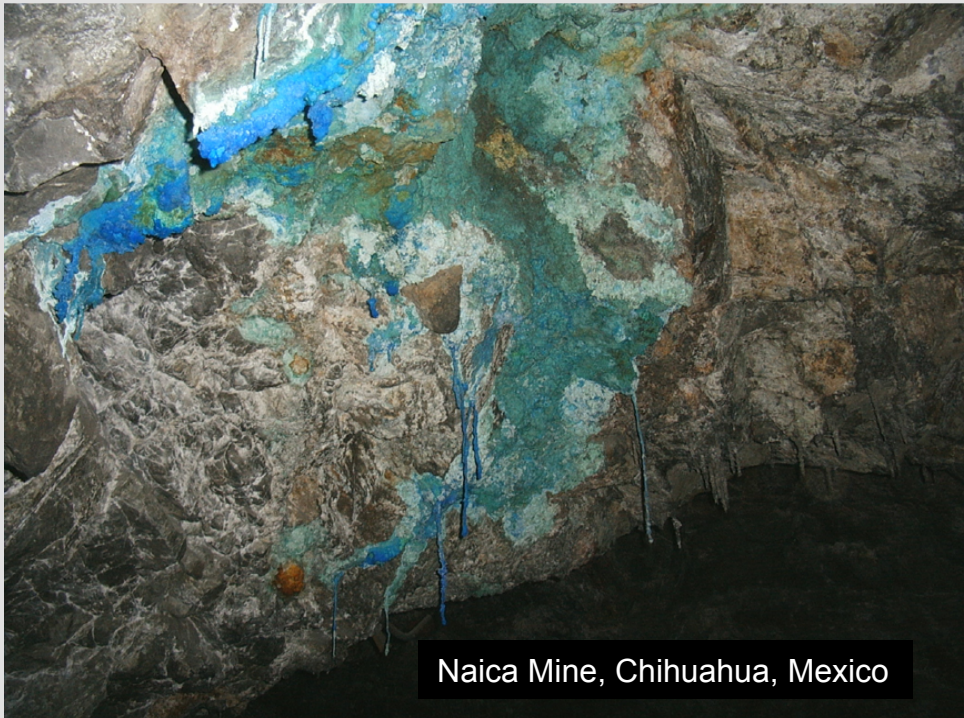
Mine Cave
Sardinia, Italy



Malequita Cave,
Venezuela



Maelstrom Lavatube, Hawaii

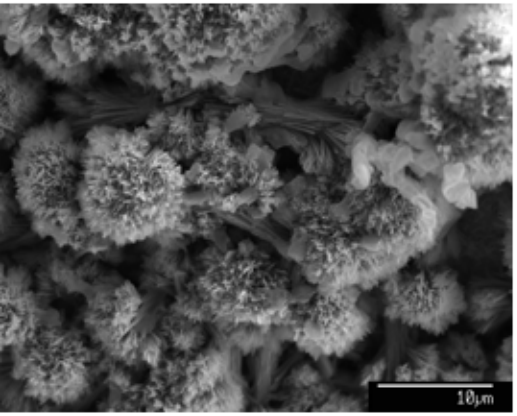


Naica Mine, Chihuahua, Mexico

30 months after inoculation growth is visible

4.5 years significant mineral precipitation

Fungal/bacterial consortium
Copper sulfide oxidizer bacteria
Elemental copper stored in fungal hyphae
Copper oxides produced (malachite, azurite)

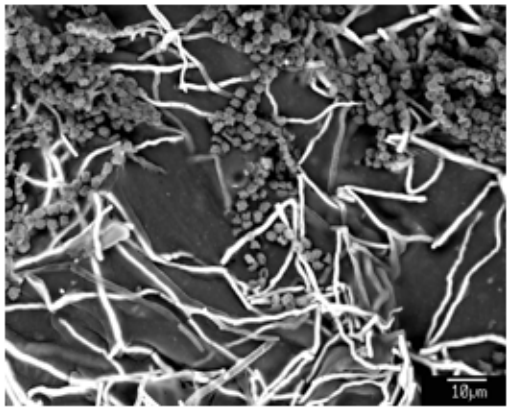


~~*Now at 8 yrs…*~~

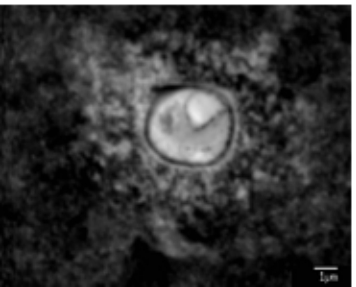
~~Now at 13 yrs!~~

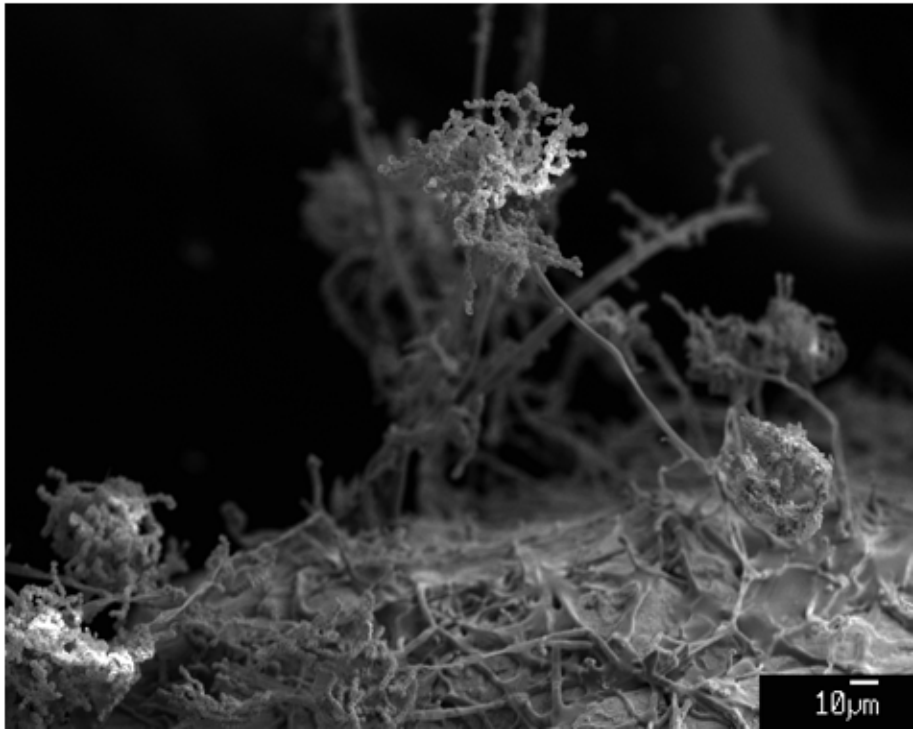
Now at 17 yrs!

SEM backscatter



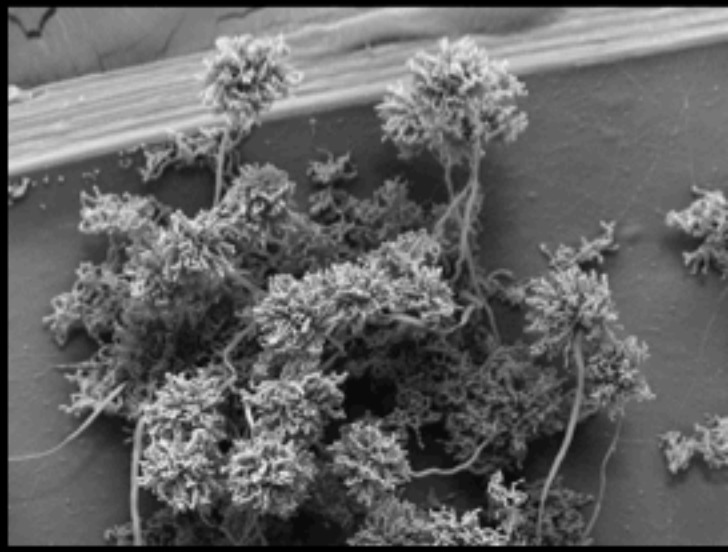
TEM





The Microbes That Wouldn't DIE!!!!!

Air Dried
Vacuum Dried, ~100°C
Coated in Au/Pd
Zapped repeatedly w/ electron beams in a hard vacuum!!!
2 Yrs later, back from the dead



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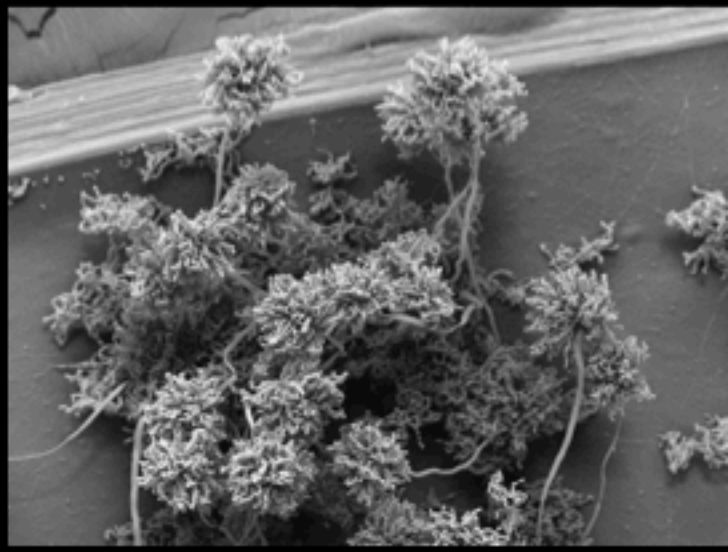
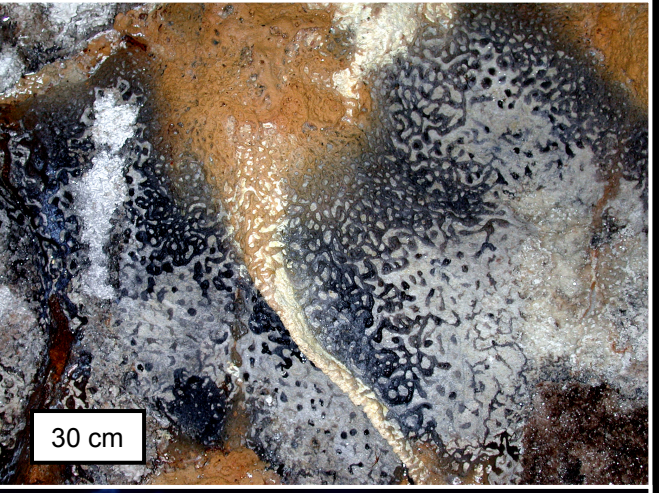
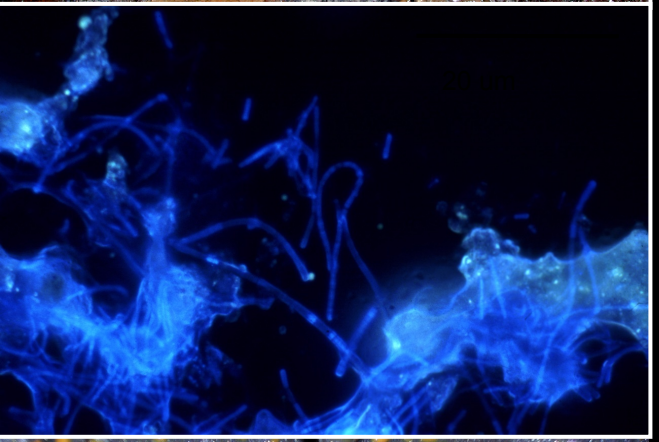


We've now done this 4 times!

Biopatterning





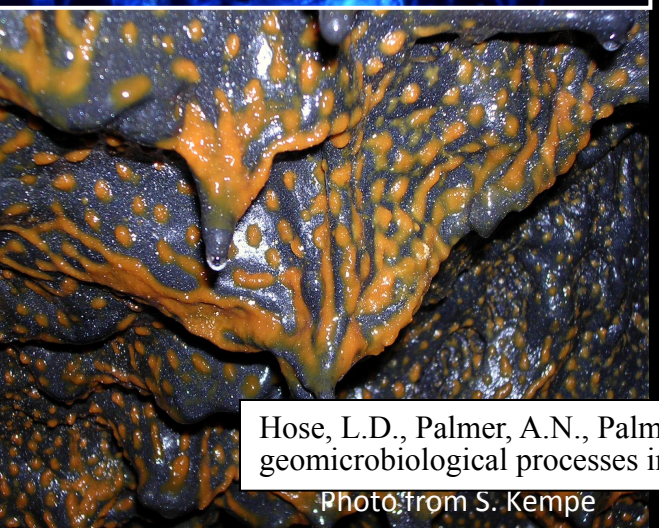
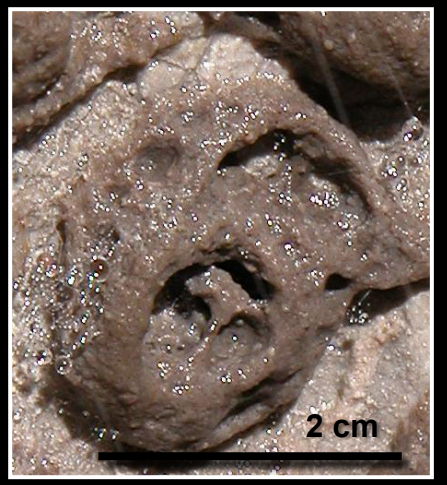


Photo from S. Kempe



Very 3D !

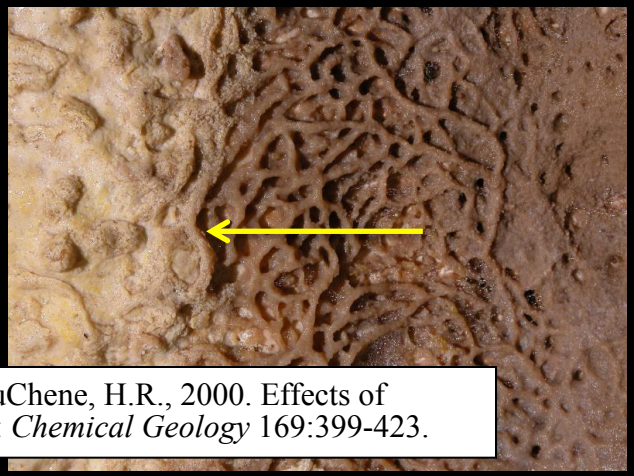
- Hieroglyphic patterns
- Biovermiculations!

- First observed in sulfuric acid cave

- Also found in Mayan ruins, mines, caves of all types including lavatubes, cryptogamic soils, under Australian hypoliths, & higher vegetation in Israel!

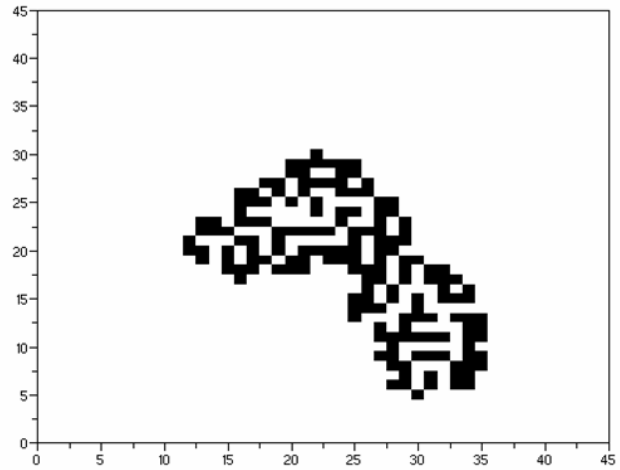
Sediment incorporation from fault gouge clays

Lithification Front

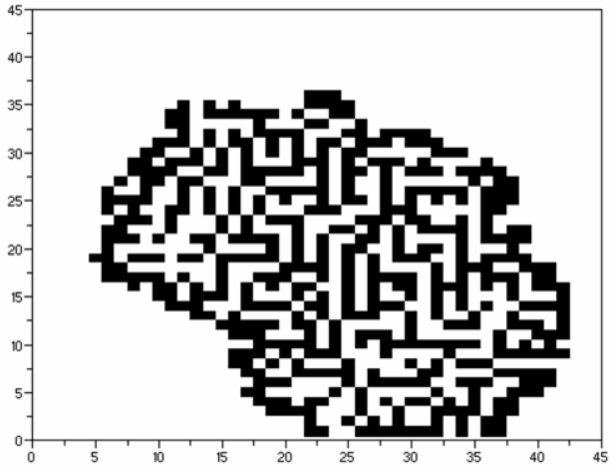


Hose, L.D., Palmer, A.N., Palmer, M.V., Northup, D.E., Boston, P.J., and DuChene, H.R., 2000. Effects of geomicrobiological processes in a hydrogen sulfide-rich, karst environment: *Chemical Geology* 169:399-423.

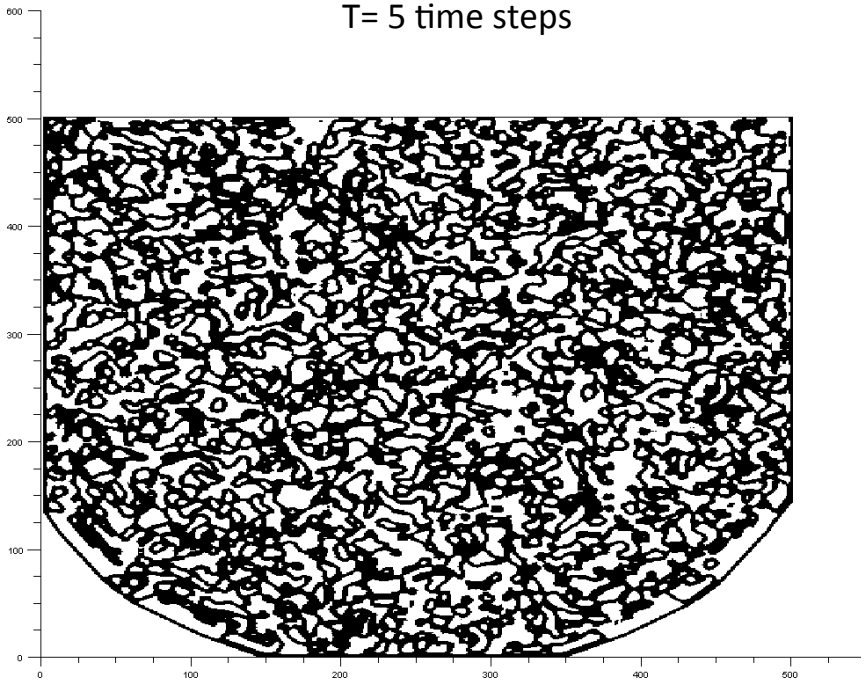
Simulated Bioverms



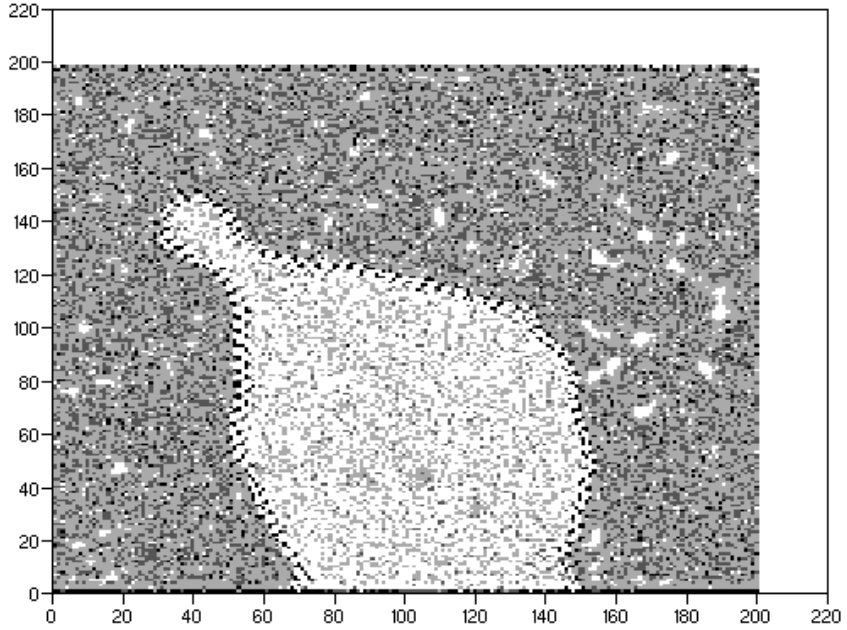
T= 5 time steps



T= 40 time steps



Proliferation from single cell row at top



Rule Set: Radius=3, Grow={27-75}, Die={0-21,21+}

Factors That Can Determine the Patterns

Physical factors

1. Gravitational gradient, can be very subtle.
2. **Laminar vs. turbulent fluid flow (moisture & nutrients governed by this)**
3. Total amount of water through system
4. Percent particulate (clay, etc.) & size distribution
5. **Binding phenomena, e.g. intrinsic viscosity, gluiness of biofilm, meshing of filaments**
6. Nature of underlying rock surface or soil (not much of a big deal)
7. Surface roughness (not much of a big deal)
8. Presence or absence of light (not much of a big deal)

Chemical factors

9. Chemical parameters (pH, salinity, etc.) (not much of a big deal)
10. **Nutrient availability (maybe a big deal)**

Biological factors

11. **Intrinsic growth geometries of organisms *(e.g. Eshel Ben Jacob, Univ. Tel Aviv)***
12. Cell wall electrical properties (dunno yet)
13. **Biotexture (e.g. filaments, clumping, etc.) (big deal)**
14. Filamentous motility *(Dawn Sumner and her team at UC Davis,* maybe a big deal)

Schubert, K., Gomez, E**.,** Boston, P., Warren-Rhodes, K., Spilde, M., McKay, C., Curnutt, J., Quintana, M., and Strader, B. 2013. Biological advantages of patterned growth. *Life.* In press.

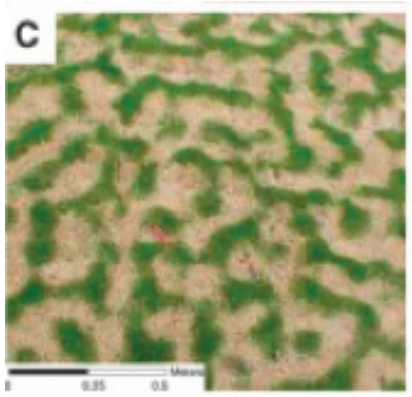
Schubert, K.E., Gomez, E., Curnutt, J. and Boston, P. 2010. To live and die in CA. In Hamid R. Arabnia and Mary Qu Yang, editors, *Proceedings of the 2010 International Conference on Bioinformatics and Computational Biology*.

Strader, B., Schubert, K., Quintana, M., Gomez, E., Curnutt, J., and Boston, P. 2010. Estimation, modeling, and simulation of patterned growth in extreme environments. In, *Software Tools and Algorithms for Biological Systems*. Springer Verlag. 550 pp.

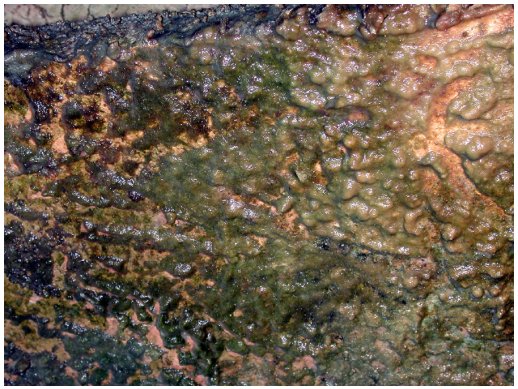
Boston, P.J., Curnutt, J., Gomez, E., Schubert, K., Strader, B. 2009. Patterned growth in extreme environments. In, *Proceedings of the Third IEEE International Conference on Space Mission Challenges for Information Technology*, pages 221-226, EES Press.

I think once we really figure out what we are doing it can help stromatolite people, ancient mat people, cryptogamic soil people, lichen people, marimo people, maybe even concretion people, and whatever else…

Teeny tiny bioverms under a hypolith, Strzelecki Desert, Australia



Higher plants in desert in Israel. Rietkerk et al. 2004. *Science* 305:1926-1929.



On Mayan ruins at Palenque, Mexico.

Very Long Term Survival of Microorganisms in Geological Materials?

What is the potential?

✧ "Entombed" longevity?

Highly controversial, ices, salt subject to plastic deformation & flow

Difficult to demonstrate or exclude contamination potential

Naica results seem credible, we are now trying it with older materials.

✧ How long can you last?

✧ How long can you be viable?

✧ Does the subsurface act as a geological genome "bank"?

- *Organisms are buried or trapped in rock time capsules*
- *Some small fraction remain viable over geologically significant time*
- *Re-exposed to the surface via geological processes*
- *"Banked" genes reintroduced to the surface microbiosphere*

✧ Earth has a chemically, hydrologically & biologically well-mixed Critical Zone

✧ Does it also have a geologically & temporally well-mixed Critical Zone?

One's perspectives change with age and experience….
(and funding and NOT funding!)

8-year-old Penny's Astrobiology

I'm a baby alien who wants to be your pet!

Delicate Elderly Scientist Penny's Astrobiology

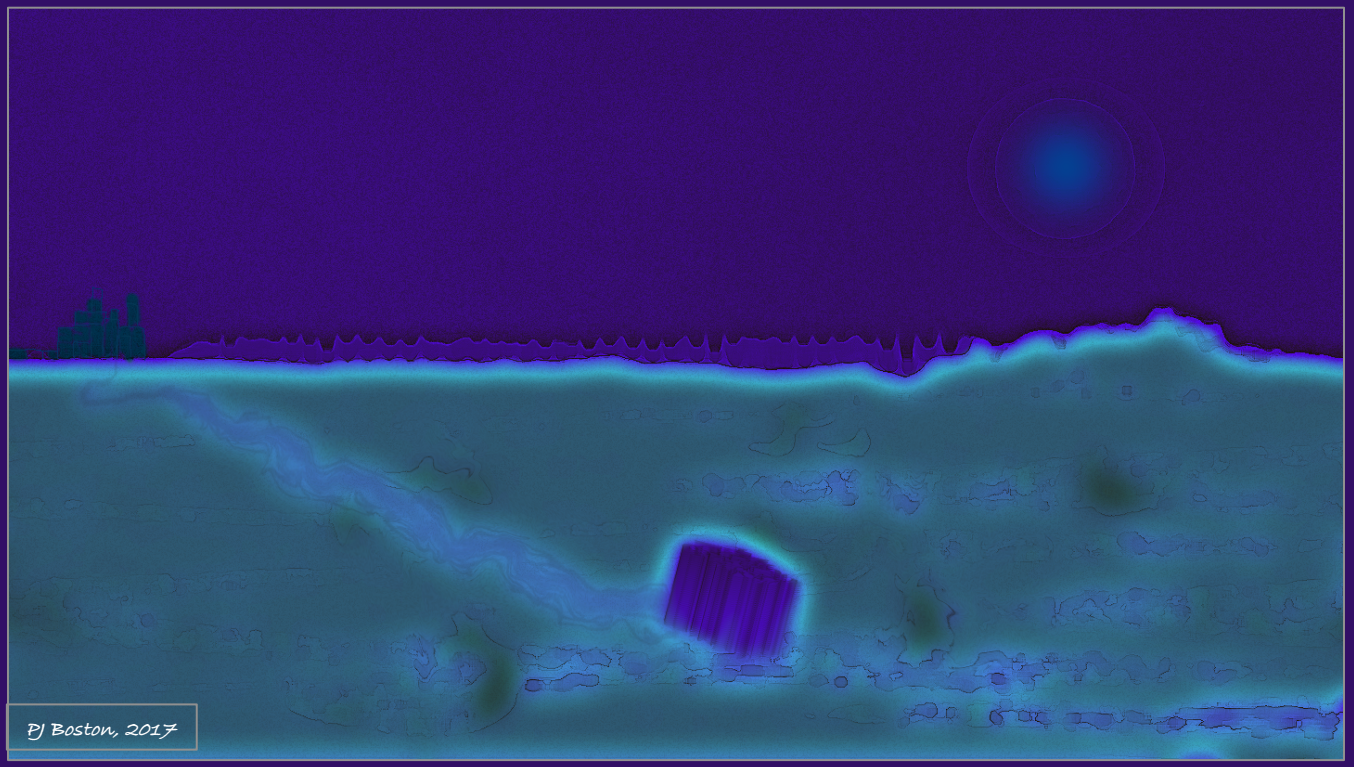
Still hoping we find something like this before….

Try not to lose the magic
In the tyranny of the immediate.

Question Time

Walking the Herd
PJ Boston, 2017

The Tricorder: Can We Really Develop It?



The Device Escapes the Factory Under a Blue Moon