Preservation of Microbial-Mineral Biosignatures in Caves & Other Subsurface Habitats

Antofagasta, Chile

Penelope J. Boston

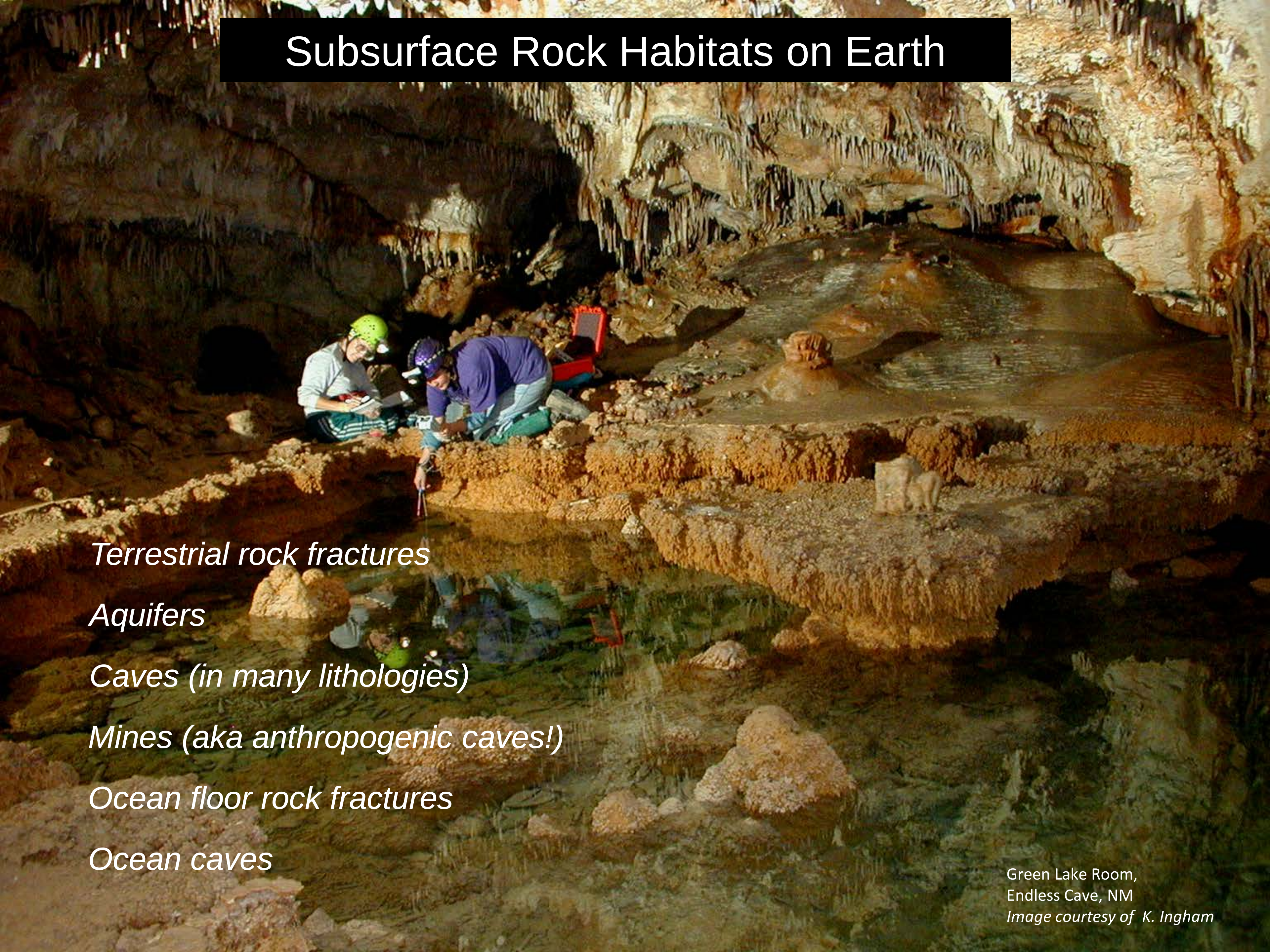
Director, Cave & Karst Studies
Chair, Earth & Environ. Sci. Dept.
New Mexico Inst. Mining & Technology
Socorro, NM
&
Associate Director
National Cave & Karst Res. Inst.,
Carlsbad, NM

After May 31st
Director, NASA Astrobiology Institute
NASA Ames Research Center
Moffett Field, CA

E. Calvin Alexander

Earth Sciences Dept.
University of Minnesota, Minneapolis, MN

& a Cast of Thousands!



Subsurface Rock Habitats on Earth

Terrestrial rock fractures

Aquifers

Caves (in many lithologies)

Mines (aka anthropogenic caves!)

Ocean floor rock fractures

Ocean caves

Green Lake Room,
Endless Cave, NM
Image courtesy of K. Ingham

What Do We Know About ET Caves?

knowledge

- Lava tubes & pits on a number of bodies

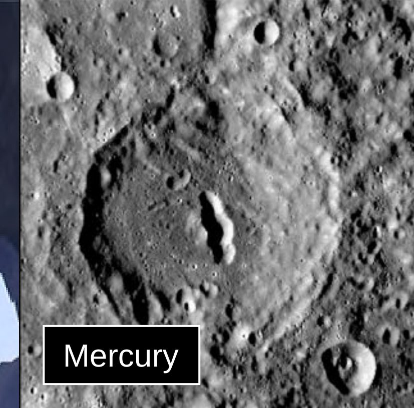
- Any planet with a surface will develop cracks
- Cracks provide the foundation for:
  - *Tectonic caves*
  - *Solutional caves (e.g. limestone, gypsum, salt)*
  - *More exotic cave-formation mechanisms*

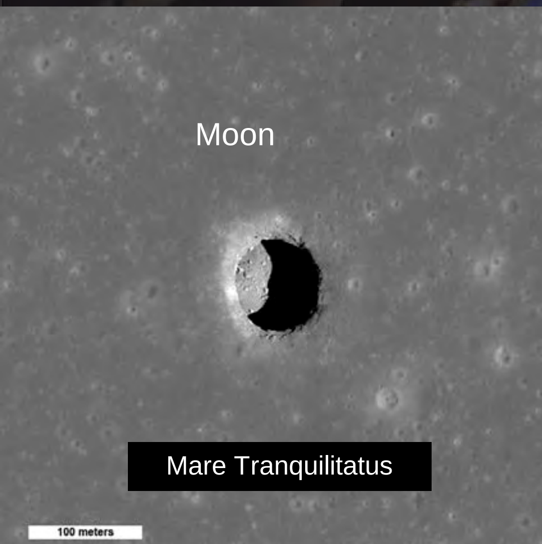
- Caves from entirely non-Earth mechanisms?
  - *e.g. sublimation of cometary ices?*
  - *Suffosion in Martian poles?*
  - *Titan karst in tholin organic goo?*

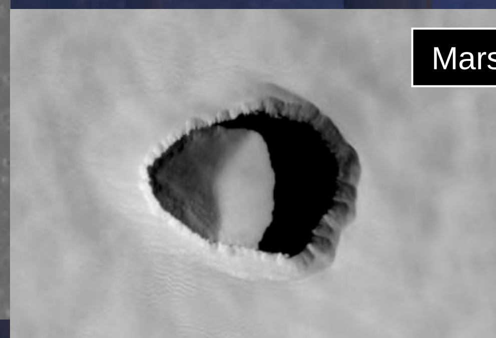
speculation

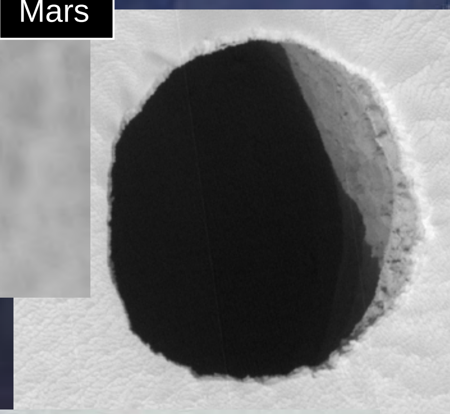
Caves of Europa, P.J. Boston

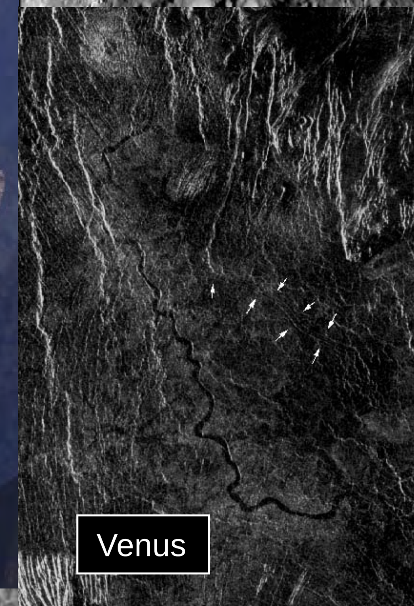
Extraterrestrial Lavatubes & Pit Caves

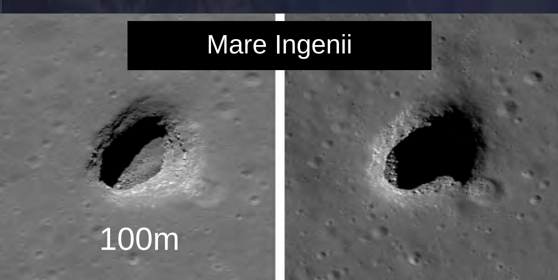


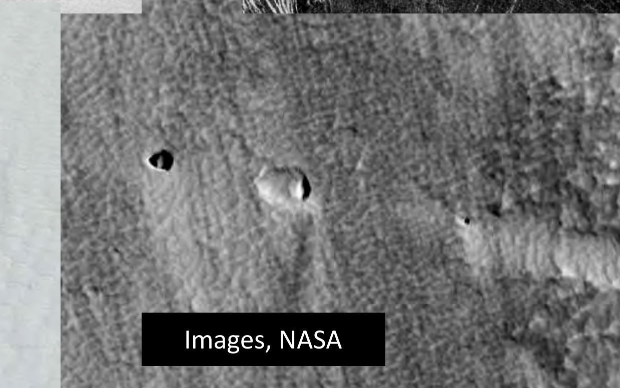












Boston, P.J. 2004. Extraterrestrial Caves. *Encyclopedia of Cave and Karst Science*. Fitzroy-Dearborn Publishers, Ltd., London, UK. Pp. 355-358.

The Planet Within

Caves & mines provide a window into a subsurface that is radically different from the surface

Rub al Khali (Empty Quarter)
Saudi Arabia, Oman, Yemen, and United Arab Emirates

Images courtesy of J. Pint

Subsurface Environmental Challenges & Benefits

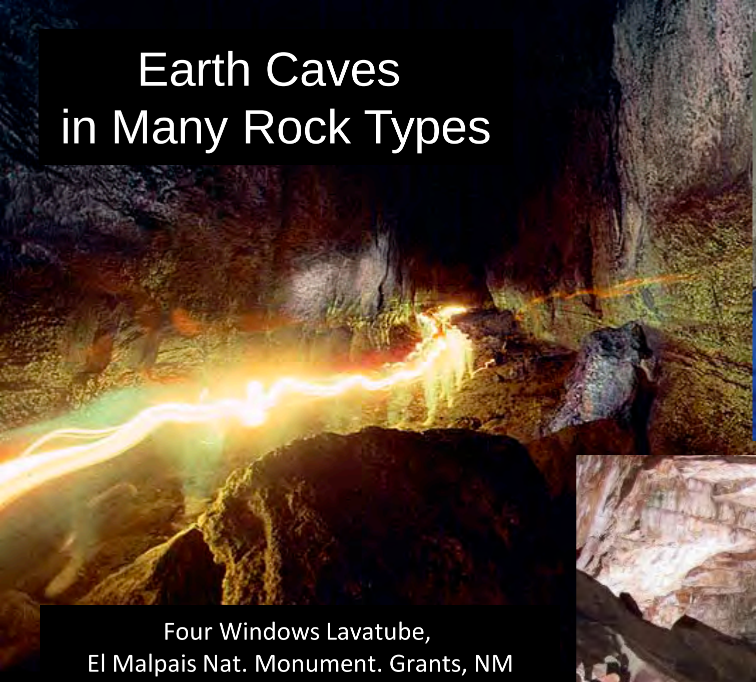
- No sunlight (past the twilight zone)
- High humidity
  (99-100% typical even in deserts)
- Temperatures constant
  (but large range globally & with depth)

- Low organic nutrients (usually)
- Mineral-rich (usually)
- Sometimes availability of extra chemical energy
  e.g. reduced gases, bedrock components

- No surface weather
- Splendid preservation environment!
- Microbial communities often self-fossilizing!
- No burial diagenesis necessary!

Entrance Drop
Lechuguilla Cave, NM
Image courtesy of David Jagnow

Earth Caves in Many Rock Types



Four Windows Lavatube,
El Malpais Nat. Monument. Grants, NM

Granite spalling caves
Gallicia, Spain

Lechuguilla Cave, Carlsbad, NM
created by sulfuric acid and limestone

Cueva de Charles Brewer
Quartzite Cave, Venezuela

Antarctic caves in ice

Caves in Salt
Atacama Desert, Chile

Submarine caves
Costa Rica

Lilburn Marble Cave, CA

Parks Ranch Gypsum Cave,
Carlsbad, NM

Process-based Cave Classification

CAVE TYPE	Dominant Processes	Parent Materials	Earth Examples	Possible Extraterrestrial Variations
Solutional	**Dissolving rock by solvent** ***(With or without chemistry)***	**Soluble solids plus a solvent**	**Classic karst, gypsum, halite**	**Non-water solvents, different thermal regimes**
Erosional	**Mechanical abrasion via wind, water, grinding, crystal wedging, etc.**	**Any solid**	**Sea coast caves, Tafonation, Aeolian rock shelters, etc.**	**Non-Earth erosional processes, e.g. radiation sputtering, frozen non-water volatile wedging**
Tectonic	**Fracturing due to internally or externally caused earth movements**	**Any rocky solid**	**Seismic caves**	**Tidal flexure from a massive primary planet or sun, impact fracturing in craters**
Suffosional	**Cavity construction by the fluid-borne motion of small particles**	**Unconsolidated sediments**	**Mud caves, some thermokarst**	**Ground ice sublimation (?) pocking at Mars poles**
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)**	**Perihelionic sublimation of frozen volatiles in comets (Temple), frozen bubbles in non-water ices, non-basalt lavatubes (Io)**
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**	**Crystallization in non-polar ices leaving voids?**

Modified from P.J. Boston 2004. Extraterrestrial Caves. In, *Encyclopedia of Caves and Karst, J. Gunn, ed.*
Titus & Boston, 2012. Interdisciplinary research produces results in the understanding of planetary caves. *EOS Trans. 93(20):196.*

Process-based Cave Classification of Target Bodies

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 structure**	Earth Mars

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.

Sulfuric acid (pH=0), H_2S, CO, & other reduced gases

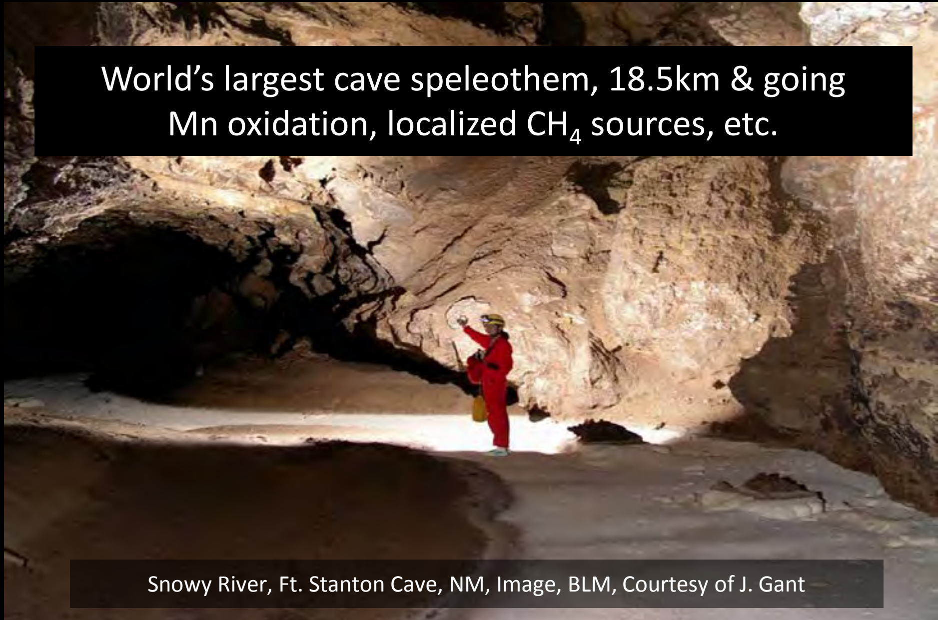
Cueva de Villa Luz, Tabasco, Mexico. Image courtesy of National Geographic Society

-3^{o}C, SO_2 , CO_2, CO & other gases

Fumarolic Caves in ice, Mt. Rainier, WA. Image courtesy of E. Cartaya

40-60^{o}C, 100% Rh

Naica Caves, Chihuahua, Mexico



World's largest cave speleothem, 18.5km & going
Mn oxidation, localized CH_4 sources, etc.

Snowy River, Ft. Stanton Cave, NM, Image, BLM, Courtesy of J. Gant

Cave Biosignature Types

Type

✧ Macroscopic biominerals

- *Textures (3D, micro & macroscopic)*
- *Minerals unique to organism influences*

✧ Microscopic microbial body fossils

- *Permineralization*
- *Entombment*

✧ Macroscopic biopatterns

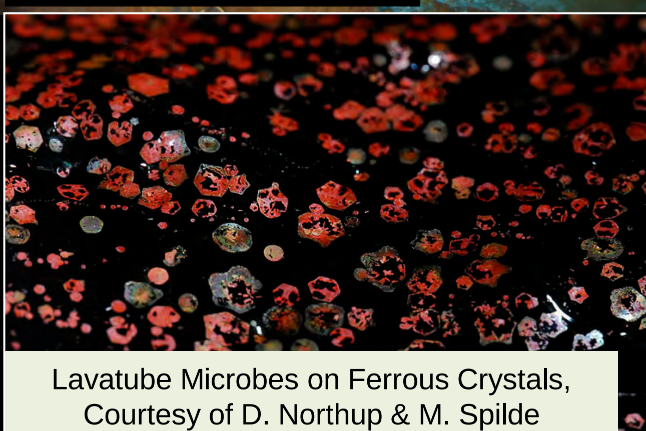
- *Biospeleothems*
- *Biovermiculations*

Cave Biosignature Types

Type	**Detectability**
✧ Macroscopic biominerals - *Textures (3D, micro & macroscopic)* - *Minerals unique to organism influences*	Easy-ish but proof is difficult
✧ Microscopic microbial body fossils - *Permineralization* - *Entombment*	Hard to do robotically but may be proof-robust
✧ Macroscopic biopatterns - *Biospeleothems* - *Biovermiculations*	Easy & obvious if you actually found some! IF no abiotic counter-examples

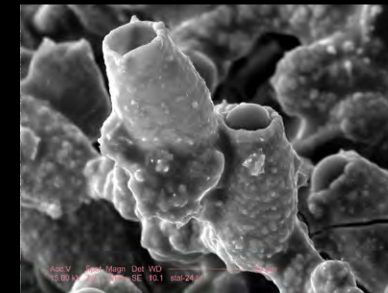
Biospeleothems

The Hunt for Blue Goo
Copper Subsurface Organisms

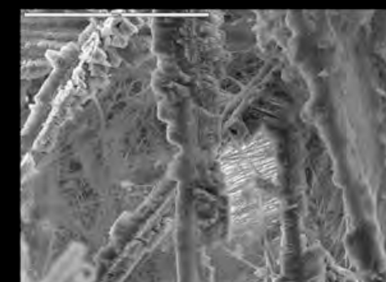


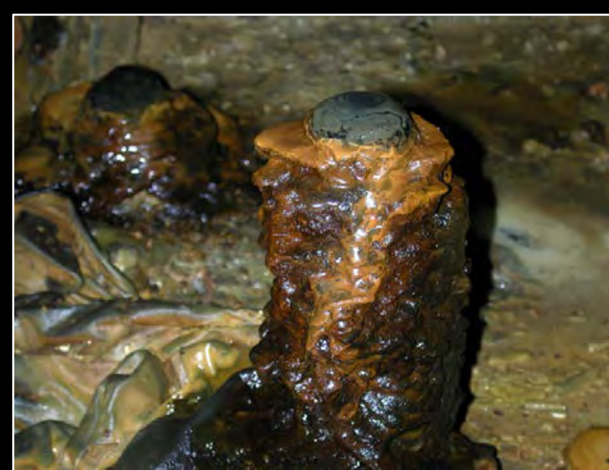
Lavatube Microbes on Ferrous Crystals,
Courtesy of D. Northup & M. Spilde

Red Tulip Microbial Iron Stalagmites,
Zoloushka Cave, Ukraine

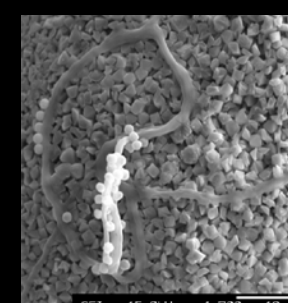


Poofball Sea, Thrush Cave,
SE Alaska

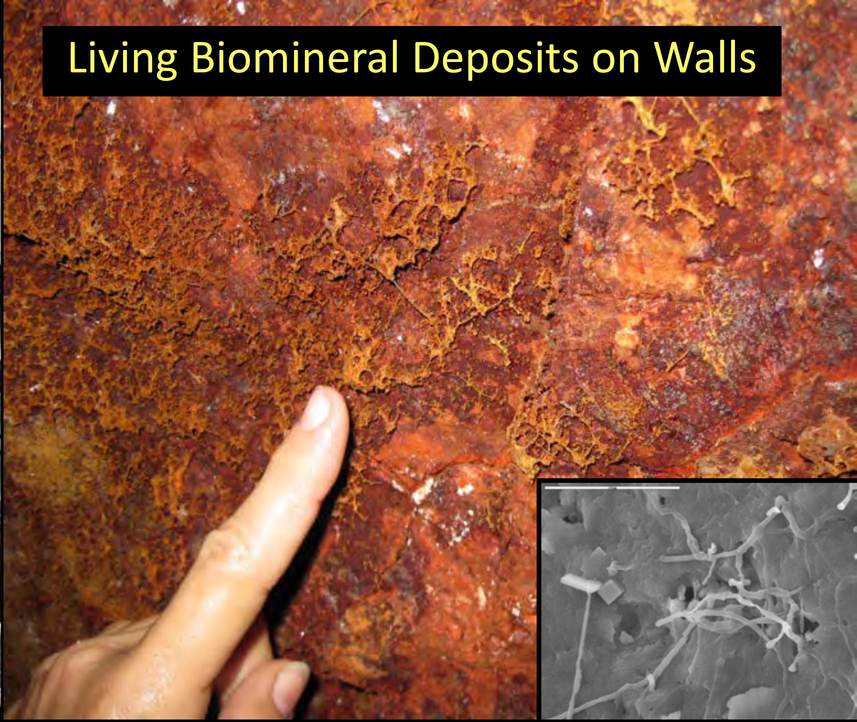


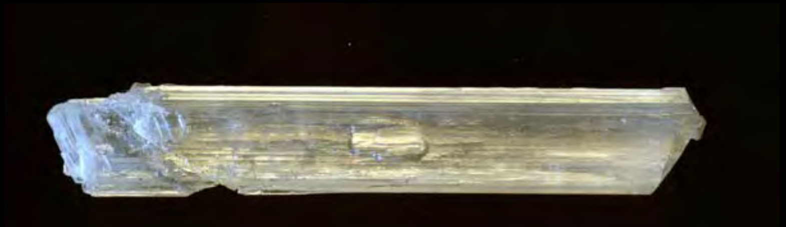


Manganese Microbe Stalagmite on
Miner's Jacket, Soudan Mine, MN

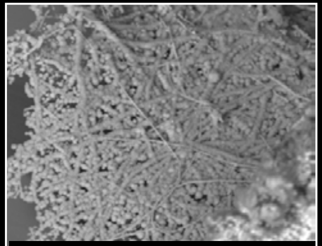


SEMs by M. Spilde & P. Boston

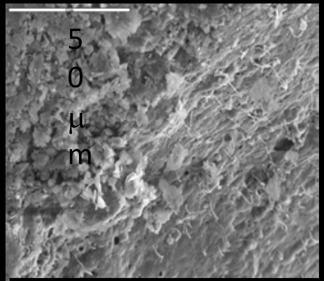




Inclusions – Pockets in the mineral



Fossil microbes



Living microbes

How long can you or your traces be detectable in geological materials???

- Results so far....
- Xtals ~500, 000+ yrs old
  (Forti et al., Lauritzen et al.)
- Sampled inclus. ~10-50k yrs old
- DNA directly recovered & sequenced, ~ 40+ strains
- 60+ live cultures growing!
- Many viruses present!
  (Suttle, Chan, Winget at UBC)

Biovermiculations (Mazelike Patterns Caused by Life)

We first discovered them in the sulfuric acid saturated cave in Mexico.
We thought they somehow had something to do with the sulfur chemistry.

But then we began to find them in many other cave and surface environments.

We found them on the walls of Mayan ruins….

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.

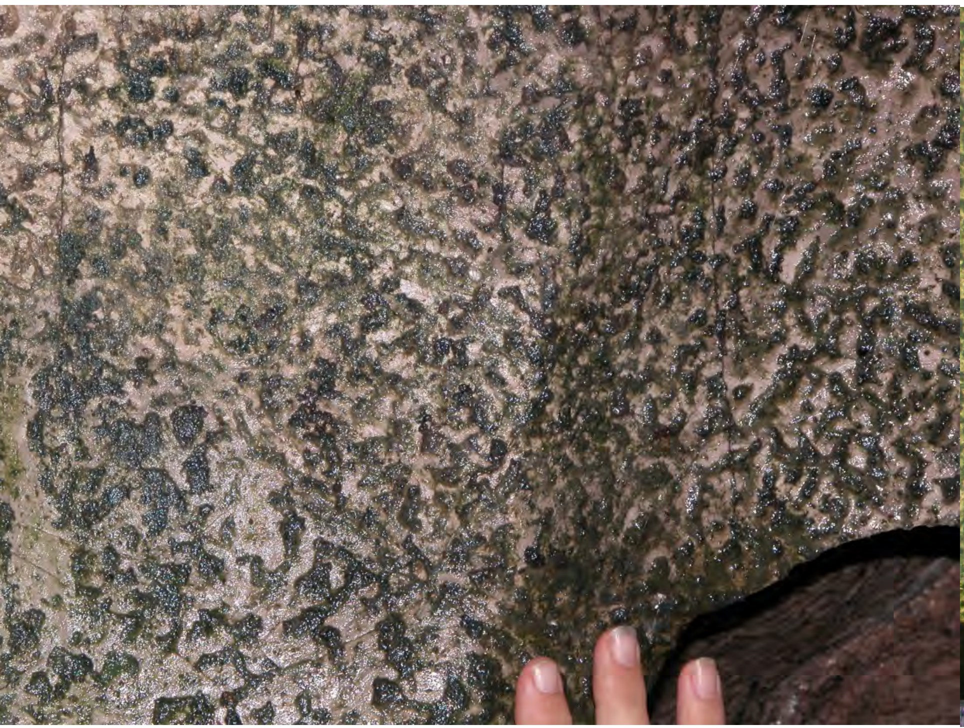
In lavatube caves in Hawaii, New Mexico, the Azorean Islands, Mexico, Italy…

Kula Kai Lava Cave, Hawaii
Image, K. Ingham

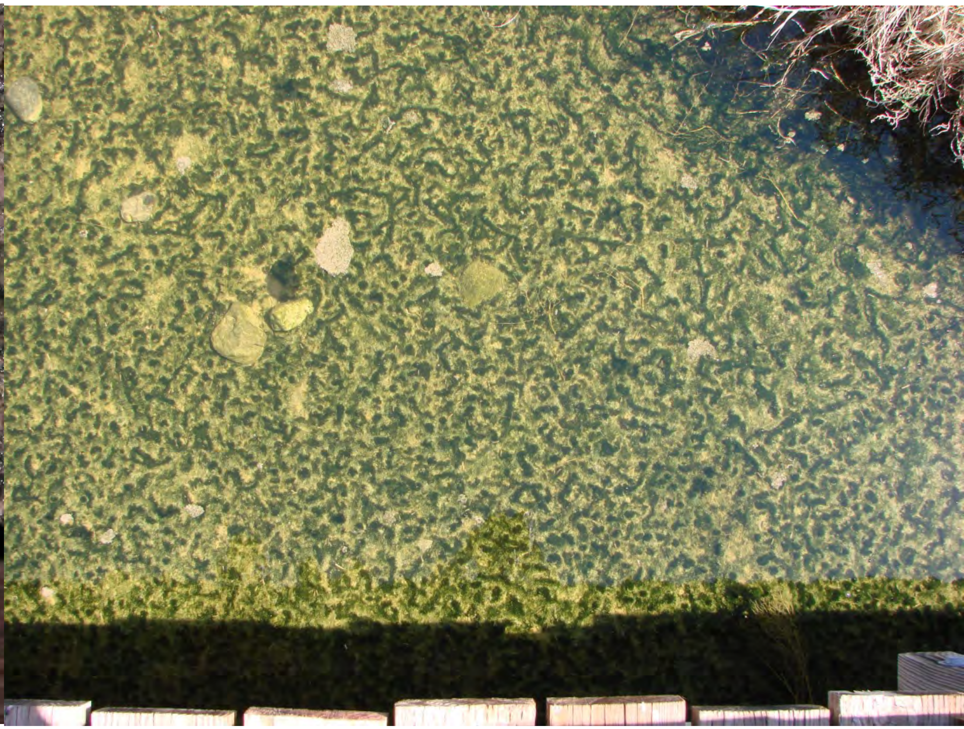
Lava Cave, Galapagos Islands, Ecuador
Image, V. Hildreth-Werker

Not Just in Caves, but Surface Too!

We found biovermiculations dominated by photosynthetic microorganisms in lighted cave entries, and on the bottom of a saline desert stream….



Twilight Zone, Cueva de Villa Luz, Mexico
Image, K. Ingham

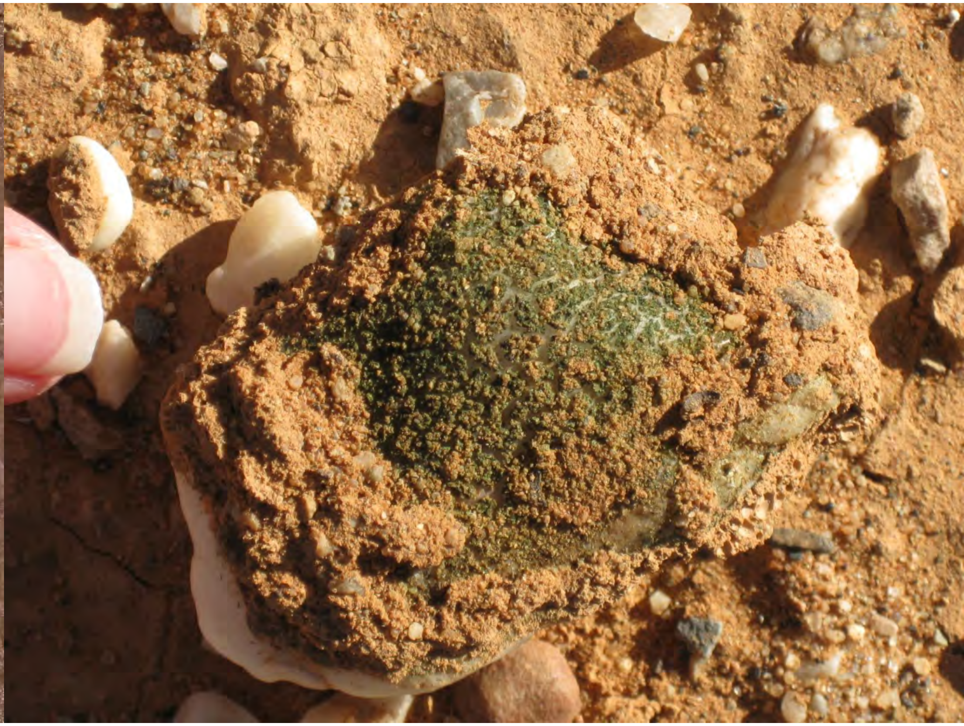


Saline Creek, Death Valley, CA
Image by K. Schubert

We found living biovermiculations lithifying to become fossils in real-time.

We found very tiny scale (sub mm) biovermiculations in cyanobacterial hypoliths on the undersides of translucent rocks in deserts in Australia, Chile, California, and New Mexico.

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



Underside of hypolithic rock, Strzelecki Desert, Australia

Are there abiotically produced patterns that mimic bioverms?

We realized we were seeing the same patterns in cryptogamic desert soils.

We found a paper (Rietkirk et al. 2004) that reported similar patterns in higher vegetation in deserts. And we began to see those patterns also.

Cryptogamic soils, Mojave Desert, CA

Desert Grasses, Mojave Desert, CA

The nature of the chemistry didn’t seem to matter.

(e.g. sulfur rich, carbonate, iron & manganese, heavy metals, hyperacidic and saline environments, etc.)

Temperature didn’t matter.

Hot, cold, “just right”…

The nature of the bedrock didn’t seem to matter.

(e.g. basalt, limestone, granite, quartzite, gypsum, soil, etc.)

The identities of the organisms didn’t seem to matter.

(e.g. prokaryotic photosynthesizers, heterotrophs, chemotrophs, protists, fungi, lichens, and even higher plants!)

Even the spatial scale doesn’t seem to matter!

So what DOES seem to matter……?

Most Promising Factors We Suspect…

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

1. Chemical parameters (pH, salinity, etc.) (not much of a big deal)
2. Nutrient availability (maybe a very big deal)

Biological factors

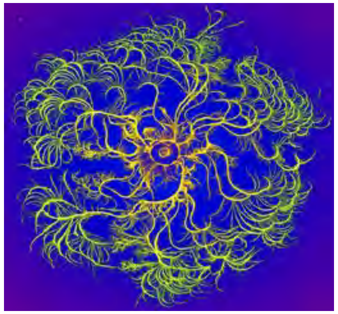
3. Intrinsic growth geometries of organisms *(e.g. Eshel Ben Jacob, Univ. Tel Aviv)*
4. Cell wall electrical properties (dunno yet)
5. Biotexture (e.g. filaments, clumping, etc.) (big deal)
6. Filamentous motility *(Dawn Sumner and her team at UC Davis,* probably a big deal)

Most Promising Factors We Suspect…

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 very 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,* probably a big deal)

We decided that all this probably meant something real about biology…

We started to try to model the patterns.

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.

Strader, B., Schubert, K., Gomez, E., Curnutt, J., and Boston, P. 2009. Simulating spatial partial differential equations with cellular automata. In Hamid R. Arabnia and Mary Qu Yang, editors, *Proceedings of the 2009 International Conference on Bioinformatics and Computational Biology*, Volume 2, pages 503–509, July 2009.

Curnutt, J. 2010. To Live and Die in CA. Thesis. CA State Univ. San Bernardino, CA.

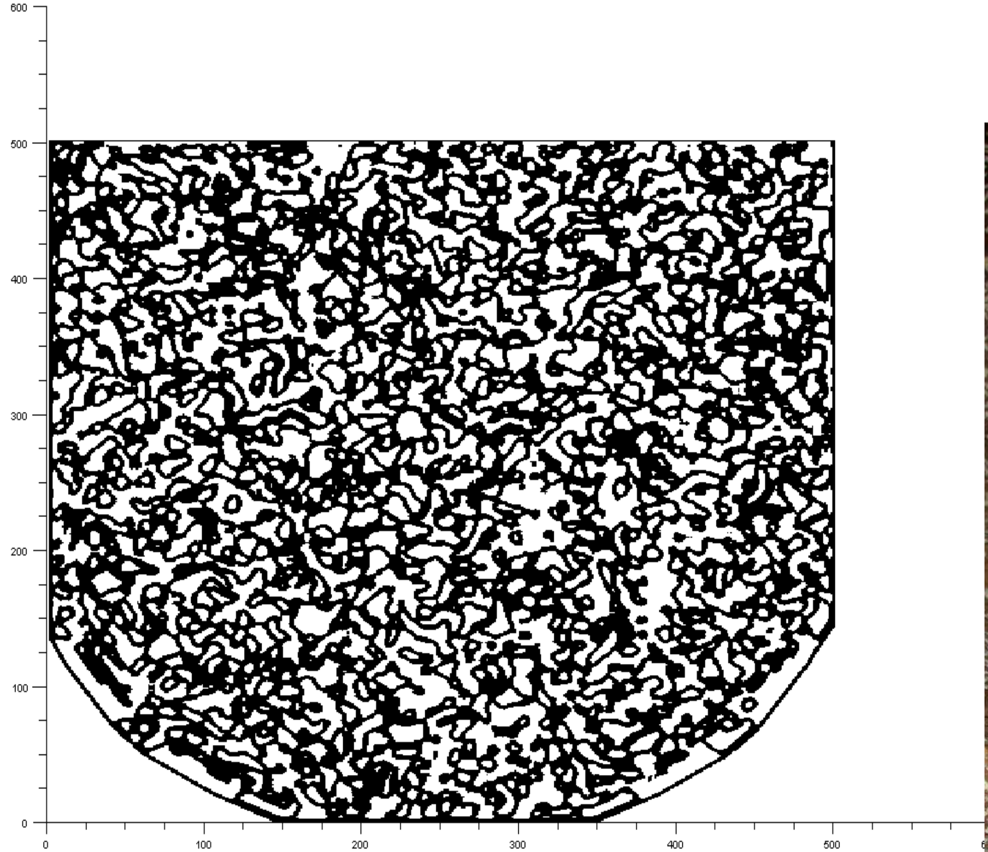
Schubert, K.E., Gomez, E., Curnutt, J. and Boston, P. 2010. To live and die in CA. In Hamid R. Arabnia and Mary Qu Yang, editors, *Proceedings of the 2010 International Conference on Bioinformatics and Computational Biology*.

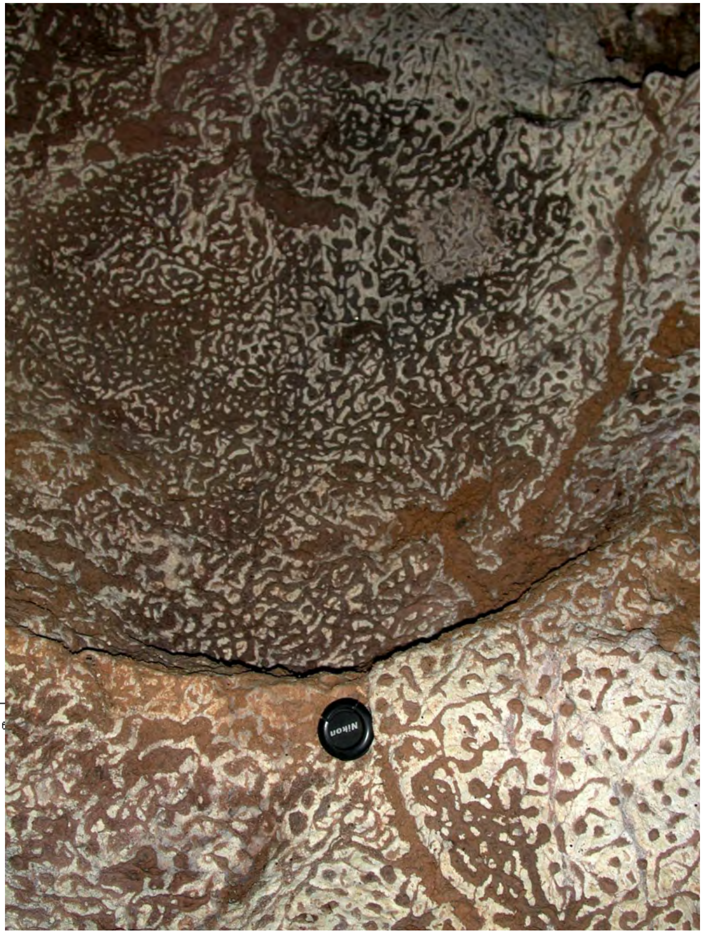
Strader, B., Schubert, K., Quintana, M., Gomez, E., Curnutt, J., and Boston, P. 2010. Simulation of patterned growth in extreme environments. In, *Software Tools and Algorithms for Biological Systems*. Springer Verlag. 550 pp.

Strader, B., Schubert, K. E., Quintana, M., Gomez, E., Curnutt, J., Boston, P. 2011. Estimation, modeling, and simulation of patterned growth in extreme environments. *Advances in experimental medicine and biology* 696:157-70. DOI:10.1007/978-1-4419-7046-6_16

Schubert, K., Ritchie, C., Gomez, E., & Boston, P. 2016. Using swarms to solve the inverse problem in cellular automata for life in extreme environments. In review. *Proc. 17th Workshop on Advances in Parallel & Distributed Computational Models.*

Simulated Bioverms





50 Rule Model

Correlate the rules with the patterns with an understanding of the surrounding environmental factors.

- Water
- Soil
- Biomass
- Symbiosis

- Weather or micrometeorology
- Randomness
- Over-crowding
- Predation/parasitism

Life	Death
1-34	**35-50**

- Air currents
- Hot & Cold Temperatures
- Sediments

We suggest that any microbial system, even one made of silica compounds (!) on Planet Zorbag in the Alpha Eridani System far far away….

…under the right conditions would produce biovermiculation patterns!

None of the factors so far identified as major pattern controllers are tied to a specific chemistry!

- **BECAUSE!**

- They are expressions of **behavior** in response to **ecological drivers!**

- **Self-organizing patterns, sensu Ashby, Prigogine, ben Jacob, etc.**

- Fluid
- Particles
- Reproducing units (i.e. growing organisms)
- Binding sticky compound or gluiness (like biofilm)
- Filamentousness

Diana Northup sampling lava cave biovermiculations in the Azorean Islands. Image courtesy of K. Ingham

Ongoing Work

✧ Time-lapse photography of patterns *in situ*

✧ Laboratory simulations of some aspects

✧ Continued modeling

✧ Detection via JPL Robotic Platform, Kelly et al poster today!

✧ **Most importantly!**

Continued search for abiotic counter-examples

Touch the earth and listen to the rocks
For they remember…
They know and remember
All that has come
to pass here.

- *Lee Henderson*

<u>Team Members:</u>

Diana Northup
Mike Spilde
Cliff Dahm
Susan Barns
Laura Crossey
Rachel Schelble
Laura Bean
Kathy Dotson
Larry Mallory
Katie Harris
Megan Curry
Kevin Stafford
Kenneth Ingham
Val H-Werker
Leslie Melim
Gus Frederick
Kathy Lavoie
Steven Welch
Jim Werker
Denise Murphy
Jodie Van de Camp
Armand Dichosa
Laura Rosales-Lagarde
Erin Kay
Lisa Majkowski

Photo courtesy of David Modisette

<u>Sponsors:</u>

National Science Foundation
NASA Inst. Adv. Concepts (NIAC)
National Cave & Karst Institute
State of New Mexico
Inst. Meteoritics, Univ. New Mexico
NASA PURSUE Program
National Geographic Society
NASA Astrobiology Program