Cave Life Overview

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What is a Cave?

*(physics version)*
Caves in Many Rock Types

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

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

Granite spalling caves
Gallicia, Spain

Caves in Halite (salt)
Atacama Desert, Chile

Lilburn Marble Cave, CA
Image public domain

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

**Compound Mechanisms * **

- **Catastrophic speleogenesis**
- **Rocky soluble solids**
- **Flynn Creek Impact**
  - Earth, Mars


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

Stratified Critical Zone?

Earth

Mars

Europa & Enceladus

Boston et al 2011, 2012
What Kind of Life Are We Looking For?

Alive….Extant Life

No Longer Alive….Extinct Life

Both!

Fossil Dinosaur Proud of Her Backbone
Biosignature Life-O-Meter

✧ **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

✧ **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
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?

Who am I? Why am I here?
What we are currently mostly doing…
Life Detection by circumstantial evidence…

- 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....
Biosignature Suites at Many Scales

The Hunt for Blue Goo
Copper Subsurface Organisms

Lavatube Microbes on Ferrous Crystals,
Courtesy of D. Northup

Phlegm ball mats
Image courtesy K. Ingham

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

snottites!
Image courtesy K. Ingham

Red Tulip Microbial Iron Stalagmites,
Zoloushka Cave, Ukraine

Poofball Sea, Thrush Cave,
SE Alaska

SEM by M. Spiide & P. Boston

suites: Microbes, minerals and Mars.
-3°C, poisonous SO₂ & other gases

World’s largest cave decoration, 18.5km & going

Sulfuric acid (pH=0), H₂S, CO, & other poisonous gases

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

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

Naica Caves, Chihuahua, Mexico, Courtesy Nat. Geogr. Soc.

40-60°C, 100% Rh

Snowy River, Ft. Stanton Cave, NM. Courtesy of FSSRSP
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

Calcite moonmilk, Crisco Passage, Spider Cave, NM


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


“Birds nests” in live moonmilk.
Iron & Manganese Auto-Fossilization

Zolushka Cave, Ukraine

Naica Caves, Chihuahua MX

5 µm
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 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

Maelstrom Lavatube, Hawaii

Mine Cave
Sardinia, Italy

Malequita Cave
Venezuela

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
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

The Microbes That Wouldn’t DIE!!!!!
The Microbes That Wouldn’t DIE!!!!!

Air Dried
Vacuum Dried, \(\sim100^\circ\text{C}\)
Coated in Au/Pd
Zapped repeatedly w/ electron beams in a hard vacuum!!!
2 Yrs later, back from the dead

We’ve now done this 4 times!
Biopatterning

- 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

Simulated Bioverms

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

Proliferation from single cell row at top

T= 5 time steps

T= 40 time steps

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)


*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…*
“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….
(\textit{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
The Tricorder: Can We Really Develop It?