The Astrobiology of the Subsurface

Caves & Rock Fracture Habitats on Earth, Mars, & Beyond

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Art: Adam Hetmansky
“What’s a Nice Girl Like You Doing in a Place Like… THAT?”

Image courtesy of T. Kieft
Unparalleled opportunity to look glamorous at all times…
• Competitively-selected science teams
  ~320 senior scientists
  ~280 postdocs and students
  ~20 US Nat Acad Sci members

• ~600 members
  ~320 senior scientists
  ~280 postdocs and students
  ~20 US Nat Acad Sci members

• ~100 participating institutions
• NAI Central - NASA Ames Research Ctr
• Programmatic– Astrobiology Program at HQ

Current Lead Institutions
• Massachusetts Institute of Technology
• University of Illinois at Urbana-Champaign
• University of Southern California
• University of Wisconsin
• VPL at University of Washington
• NASA Goddard Space Flight Center
• NASA Ames Research Center
• NASA Jet Propulsion Laboratory
• SETI Institute
• University of Colorado in Boulder
• University of California, Riverside
• University of Montana in Missoula
Astrobiology JOB 1:
Figuring out possible lifeforms from first principles!

“Ammonia! Ammonia!”

The New Yorker Magazine, Inc.
Astrobiology addresses three fundamental questions:

How does life begin and evolve?

Does life exist elsewhere in the universe?

What is the future of life on Earth and beyond?
Astrobiology = Many Sciences

- Geochemistry
- Chemistry
- Mineralogy
- Engineering
- Biology
- Physics
- Hydrology
- Geopysics
- Geophysics
- Extreme Environments
- Astronomy
- Astrobiology
Speleology = Many Sciences

- Geochemistry
- Chemistry
- Mineralogy
- Geology
- Hydrology
- Geophysics
- Paleontology
- Archaeology
- History
- Geomicrobiology
- Microbiology
- Speleology
Rock fracture habitats

- Water-storing rocks (Aquitifers)
- Caves
- Mines (anthropogenic caves!)
- Ocean floor rock fractures
- Ocean caves
Hmmm...
I keep thinking I hear zillions of tiny voices....
it must be Cave Madness!

Hey hey hey!
We’re over here!!!

Humans aren’t very smart, are they?
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 John Pint
Subsurface Environments

- No sunlight (past the twilight zone)
- High humidity
- Temperatures constant

- Low organic nutrients
- Mineral-rich
- Unusual chemical energy sources (e.g. H$_2$S)

- No surface weather
- Splendid preservation environment!
What is Geomicrobiology?

Microorganism interactions with rocks and minerals

What do microbes do?

Transform materials

Destroy bedrock

Precipitate biominerals actively & passively
Significance of Geomicrobiology

- Geological weathering agents
- Economic minerals
- Unusual minerals
- Low temperature enzymes
- Pharmaceutical potential
- Unknown organisms & biochemistry
- Origins of life & early evolution
  - AstrobioLOGY
…the search for life in the universe…

Writing the Field Guide to

Unknown Organisms

Limits to life on Earth?
Relationship to Early Earth conditions?
Potential for life on other planets?

© Slawek Wojtowicz 1997
By courtesy of the artist
Extraterrestrial Caves

By courtesy of the artist
What Do We Know About Extraterrestrial Caves?

- Lava tube caves on a number of bodies (Moon, Mars, etc.)

- Any planet with a surface will develop cracks
- Cracks provide the foundation for:
  - dissolved caves (e.g. limestone, gypsum, salt)
  - crust motion (tectonic) caves
  - cave-formation mechanisms that don’t happen on Earth

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

*knowledge*

*speculation*

*Caves of Europa, P.J. Boston*
We’ve known about extraterrestrial cave-forming processes since the dawn of the Space Age!

Extraterrestrial Lavatubes & Pit Caves

Mare Tranquilus

Mare Ingenii

100m

35 m

Martian Cave Entrance

HiRise data
30 cm resolution
Hole is 100 m across!
Martian Cave Entrance

HiRise data
30 cm resolution
Hole is 100 m across!

Compared to an American football field

HiRise Camera Image
Martian Cave Entrance

compared to an American sinkhole!
West Desert Sinkhole, Utah

~22 meters diameter
Santa Cruz Is., Galapagos Is
~80m diam volcanic collapse feature
Earth Caves in Many Rock Types

Four Windows Lavatube, El Malpais Nat. Monument. Grants, NM
Image courtesy of K. Ingham

Granite spalling caves, Galicia, Spain

Lechuguilla Cave, Carlsbad, NM
created by sulfuric acid and limestone
Image courtesy D. Bunnell

Cueva de Charles Brewer
Quartzite Cave, Venezuela
Image courtesy C. Brewer

Caves in Salt
Atacama Desert, Chile

Submarine caves
Costa Rica
Courtesy of J. Mylroie

Antarctic ice caves, Mt. Erebus
Courtesy of A. Curtis

Lilburn Marble Cave, CA

Parks Ranch Gypsum Cave, Carlsbad, NM
# Process-based Cave Classification

<table>
<thead>
<tr>
<th>CAVE TYPE</th>
<th>Dominant Processes</th>
<th>Parent Materials</th>
<th>Earth Examples</th>
<th>Possible Extraterrestrial Variations</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>Non-water solvents, different thermal regimes</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>Non-Earth erosional processes, e.g. radiation sputtering, frozen non-water volatile wedging</td>
</tr>
<tr>
<td>Tectonic</td>
<td>Fracturing due to internally or externally caused earth movements</td>
<td>Any rocky solid</td>
<td>Seismic caves</td>
<td>Tidal flexure from a massive primary planet or sun, impact fracturing in craters</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>Ground ice sublimation (?) pocking at Mars poles</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, glaciere’ caves (i.e. caves in ice as bedrock), “thermokarst”</td>
<td>Perihelionic sublimation of frozen volatiles in comets (Temple), frozen bubbles in non-water ices, non-basalt lavatubes (Io)</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>Crystallization in non-polar ices leaving voids?</td>
</tr>
</tbody>
</table>

### Process-based Cave Classification of Target Bodies

<table>
<thead>
<tr>
<th>CAVE TYPE</th>
<th>Dominant Processes</th>
<th>Parent Materials</th>
<th>Earth Examples</th>
<th>WHERE????</th>
</tr>
</thead>
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<tr>
<td>Solutional</td>
<td>Dissolving rock by solvent <em>(With or without chemistry)</em></td>
<td>Soluble solids plus <em>solvent</em></td>
<td>Classic karst, gypsum, halite</td>
<td>Earth, Titan, Mars</td>
</tr>
<tr>
<td>Erosional</td>
<td>Mechanical erosion via wind, water, grinding, crystal wedging, etc.</td>
<td>Any solid</td>
<td>Sea coast caves, tafonation, aeolian rock flutes, 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 from melt or sublimation</td>
<td>Meltable or sublimable materials capable of solidifying at planetary 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>
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**Compound Mechanisms**
- **Catastrophic speleogenesis**
- **Rocky soluble solids**
- **Flynn Creek Impact structure**


Icy Satellites…not “ocean worlds”, but planet-sized aqueous caves!
Cave Potential on Icy Bodies

- Whole planet/moon
- Pressure melt lenses (like Vostoc)
- Surface towers (like Antarctica)
- Fracture cavities (like glaciers)
- Surface cavities (like Mt. Rainer etc.)
- Plume associated cavities (sorta like Antarctica)
Ice Towers & Caves on Mt. Erebus, Antarctica & Mt. Rainier, WA
May be some on Mars, Europa, & Enceladus!

Courtesy, Eddy Cartaya

Courtesy, Aaron Curtis

Historical Photograph

Courtesy, Eddy Cartaya
Sulfuric acid (pH=0), H₂, S, CO, & other poisonous gases
Cueva de Villa Luz, Tabasco, Mexico, Courtesy Nat. Geogr. Soc.

-3°C, poisonous SO₂ & other gases
Fumarolic Ice Caves, Mt. Rainier, WA, Courtesy Eddy Cartaya

40-60°C, 100% Rh
Naica Caves, Chihuahua, Mexico, Courtesy Nat. Geogr. Soc.

World’s largest cave decoration, 18.5km & going

Snowy River, Ft. Stanton Cave, NM, Image, BLM
### What Kind of Planet Is It?

<table>
<thead>
<tr>
<th>Planet Type 1 Biosphere</th>
<th>Planet Type 2 Biosphere</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Sunlight</strong> “just right”</td>
<td><strong>No visible means of support</strong></td>
</tr>
<tr>
<td><strong>Green</strong></td>
<td><strong>Not green</strong></td>
</tr>
<tr>
<td><strong>Gooey</strong></td>
<td><strong>Not gooey</strong></td>
</tr>
<tr>
<td><strong>Gases in non-equilibrium</strong></td>
<td><strong>Gases in chemical equilibrium</strong></td>
</tr>
<tr>
<td></td>
<td><strong>Exceptions dependent upon crustal leakiness</strong></td>
</tr>
<tr>
<td><strong>Critical Zone is top-down</strong></td>
<td><strong>Critical Zone is bottom-up</strong></td>
</tr>
<tr>
<td><strong>Photosynthetically driven</strong></td>
<td><strong>Chemosynthetically driven</strong></td>
</tr>
</tbody>
</table>

Well mixed-Critical Zone

Stratified Critical Zone?

**Earth**  
**Mars**  
**Europa**
Biosignature Suites at Many Scales

The Hunt for Blue Goo
*Copper Subsurface Organisms*

Lavatube Microbes on Ferrous Crystals,
*Courtesy of D. Northup*

*snottites!* 
*Image courtesy K. Ingham*

Phlegm ball mats 
*Image courtesy K. Ingham*

Red Tulip Microbial Iron Stalagmites, Zoloushka Cave, Ukraine

Poofball Sea, Thrush Cave, SE Alaska

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

SEM by M. Spiide & P. Boston

Subsurface Inventors of New Biochemistry

 ✦ Highly partitioned environments
 ✦ Extreme isolation of habitats
 ✦ Limited mobility
 ✦ Inhibition of gene flow
 ✦ Physical limitation of space
 ✦ STRONG evolutionary pressures

Stupefying Biodiversity!
Almost everybody is new to science....

e.g. Lechuguilla Cave, NM
145 miles mapped passages so far
~ 2X that volume by argon tracer tests
100s of isolated pools
Extreme wall heterogeneity
Widely varying chemistries

Image courtesy of Peter Jones
Energy Enriched Sulfuric Acid Cave
Cueva de Villa Luz, Tabasco, Mexico

Biodiversity rich!
Biomass rich!
\( pH \) ranges from 9.2 down to 0!
Energy:
- Subsurface \( H_2S \)
- Surface-derived organics

Photos by Kenneth Ingham,
Background by Steve Alvarez

NHK 2003, etc.
Whoa! Is this a photoshop hoax?

Giant Crystal Cave - National Geographic TV Special, Oct 2008 & National Geographic Magazine, Nov. 2008
Into the Lost Crystal Cave – National Geographic TV Sequel, Oct. 2010

Image courtesy of Carsten Peters, National Geographic Society, © 2008
Naica Mine, Naica Cave System
Chihuahua, Mexico

- Giant selenite crystals (CaSO₄ same mineral as wallboard...)
- 40-60°C (105-140°F, whew!)
- Water drained for mining
- Saturated humidity
- Iron oxide deposits

Courtesy, La Venta Cave Project
- Inclusions (holes in the crystals)
- Solid & fluid
- Iron and manganese deposits on walls & in inclusions

Microbial fossils in inclusions

Live microorganisms encrusting clay & iron oxide walls

Micrographs on left, courtesy of P. Forti

Micrographs on right M. Spilde & P. Boston
Results so far....

- Xtals ~500,000+ yrs old 
  (Forti et al., Louritzen et al.)
- Sampled inclus. ~10-50,000 yrs old
- DNA directly recovered 
  & sequenced, ~ 40+ strains
- 65+ live cultures growing!
- Many viruses present! 
  (Suttle, Chan, Winget at UBC)
The Hunt for Blue Goo

*Copper Subsurface Organisms*

“Diseased” Botallackite
Harvard Mineral Museum

Malequita Cave, Venezuela

Maelstrom Lavatube, Hawaii

Naica Mine, Chihuahua
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 15 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
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

We’ve now done this 4 times!
In our cave work, we are already dealing with sensitive “alien” biology…

What are these??? Do you know? We don't....

We are finding them in caves all over the world.

Subsurface geomicrobiology is helping us to prepare for the search for life in caves on Earth, on Mars, & icy moons.

DNA analysis doesn’t help us... Too many organisms!
Exploration presents unparalleled value but also risk.
Danger Focuses the Mind!

- poisonous atmospheres
- great heat or cold
- unstable rock masses
- gear failure
- you name it

powers of observation are distilled
When exploration is coupled with the intellectual discipline of science, understanding happens.

Aaron Curtis, Warren Ice Cave, Mt. Erebus, Antarctica
“That’s all Folks!”

Wanna See My Chiggers???
Photo courtesy of Kenneth Ingham