Direct human exploration of the terrestrial subsurface

Jennifer L. Macalady, Department of Geosciences, Penn State University

Photo Ieva Perkons


view presented in coffee table books

natural state of cave room

bad air

no air (underwater passages)

no air (underwater passages)

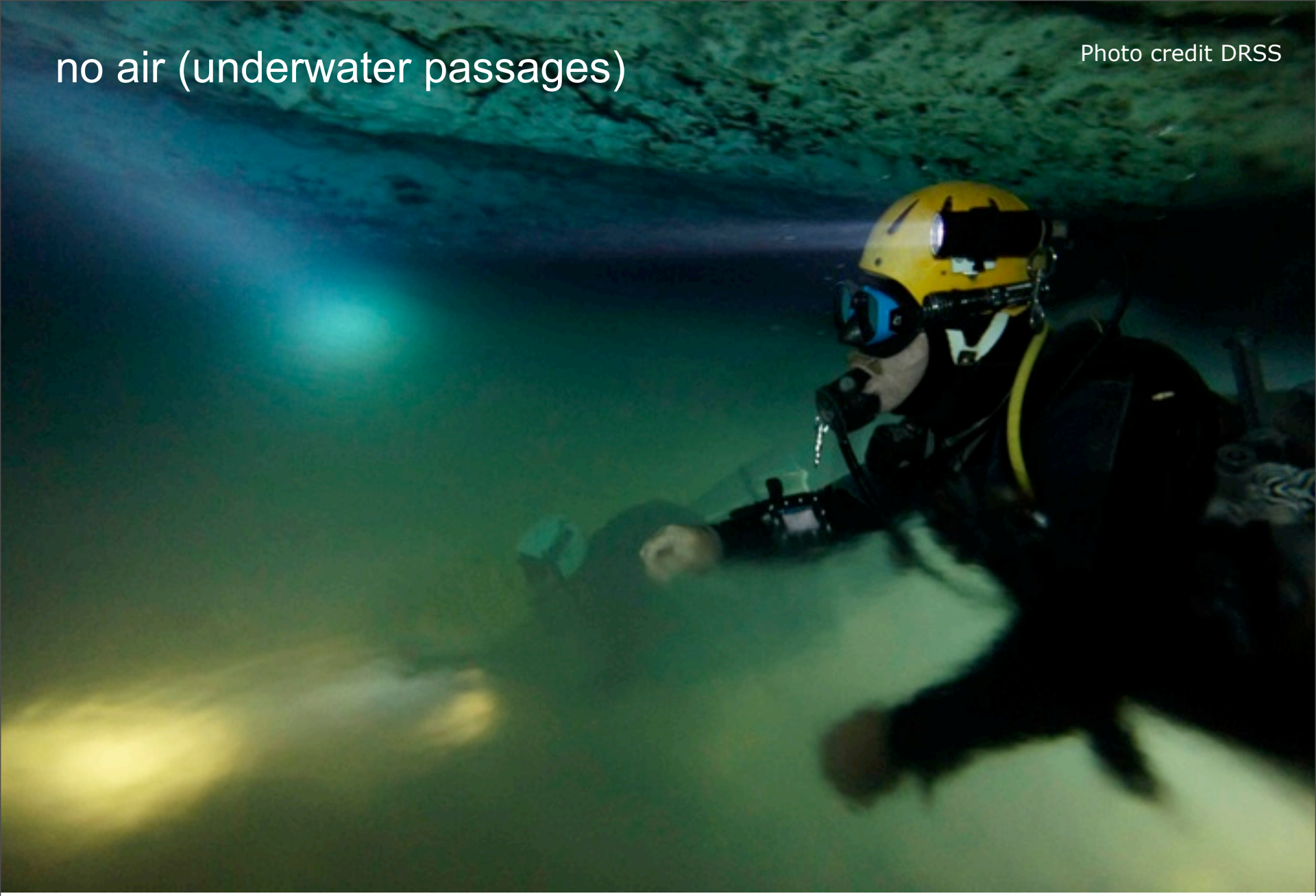


Photo credit DRSS

Manantial del Toro,
Dominican Republic


redundant life support systems
Photo J. Macalady

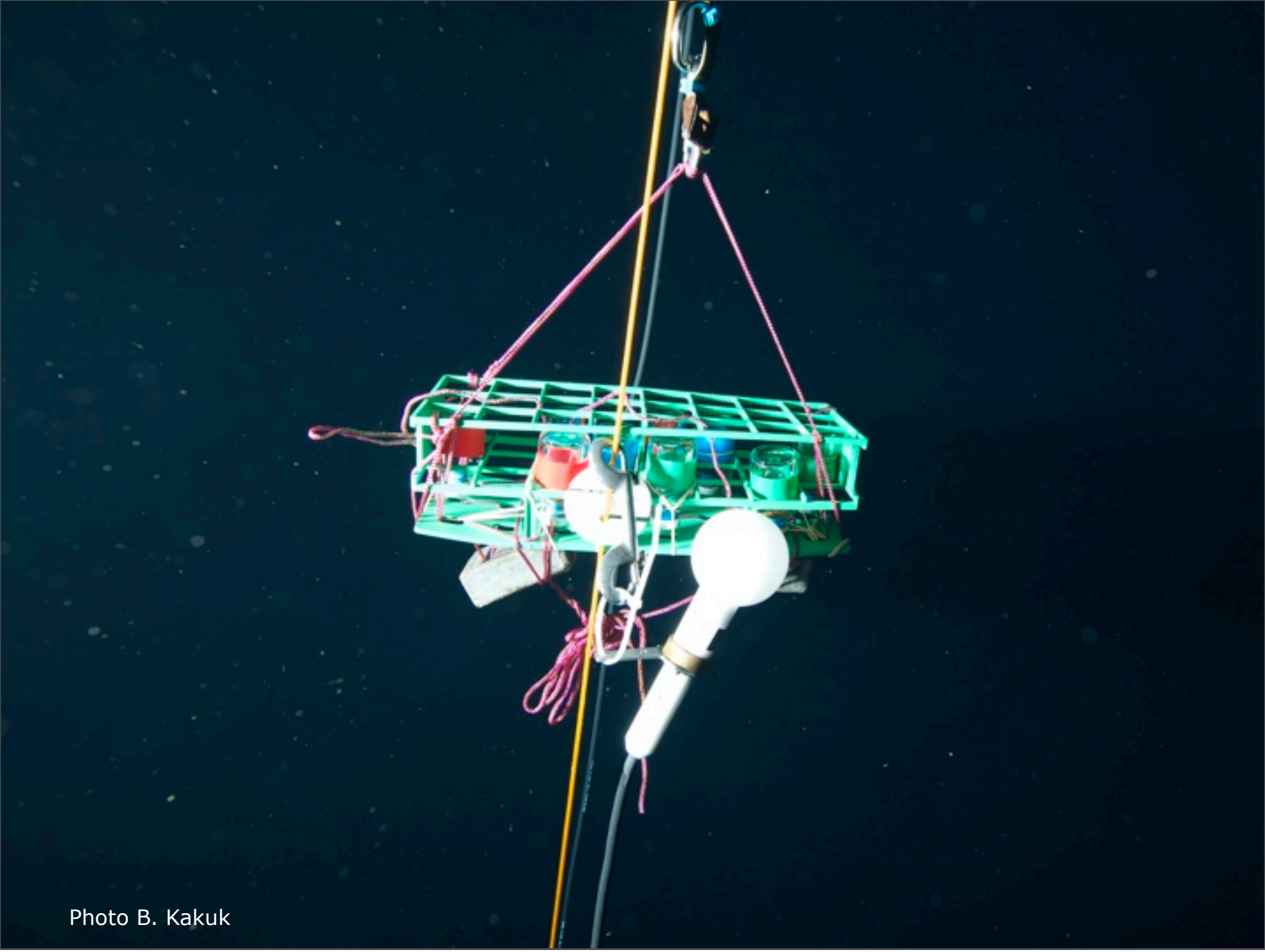


Photo B. Kakuk


Photo Victoria Alexandrovna

Manantial del Toro,
Dominican Republic

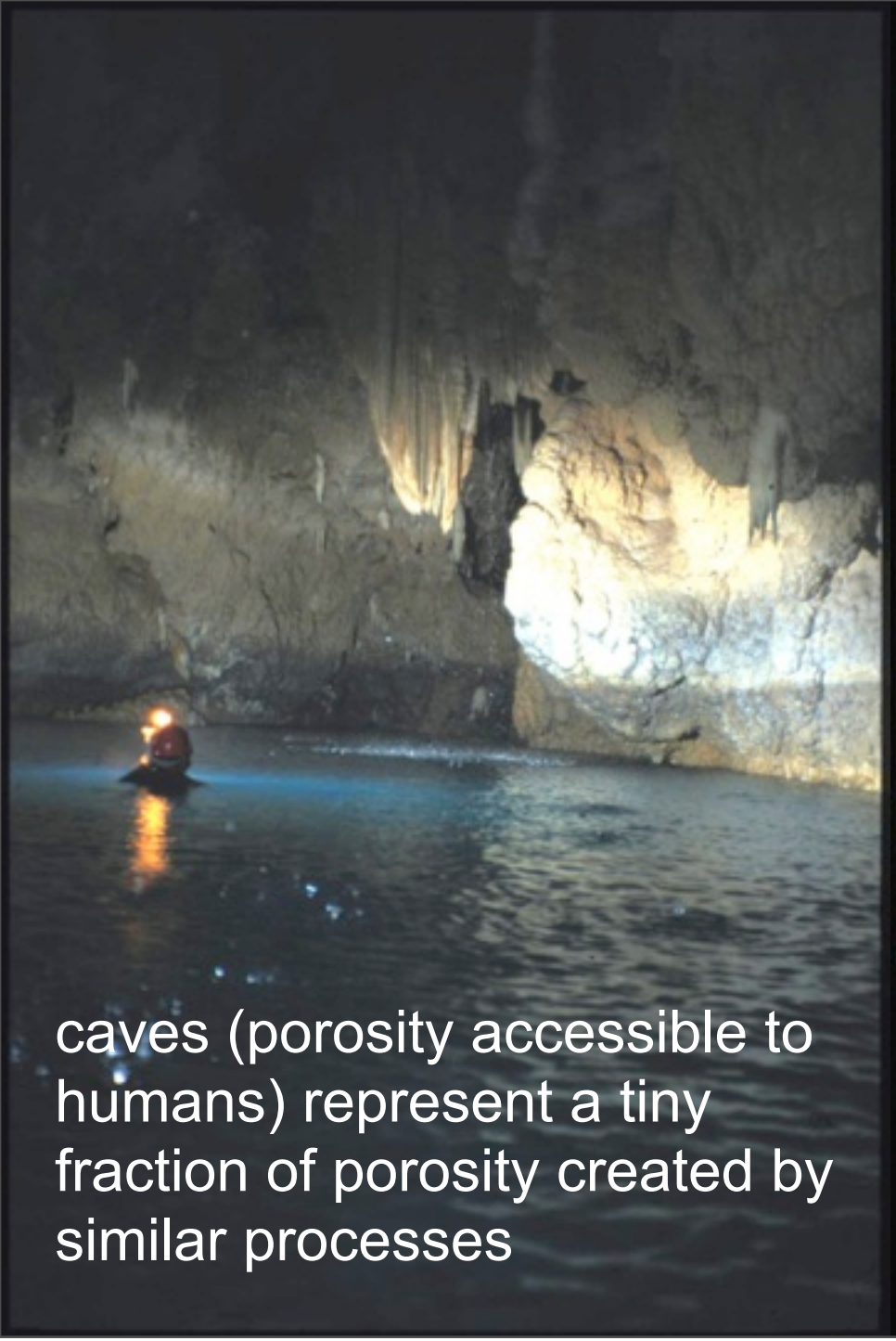


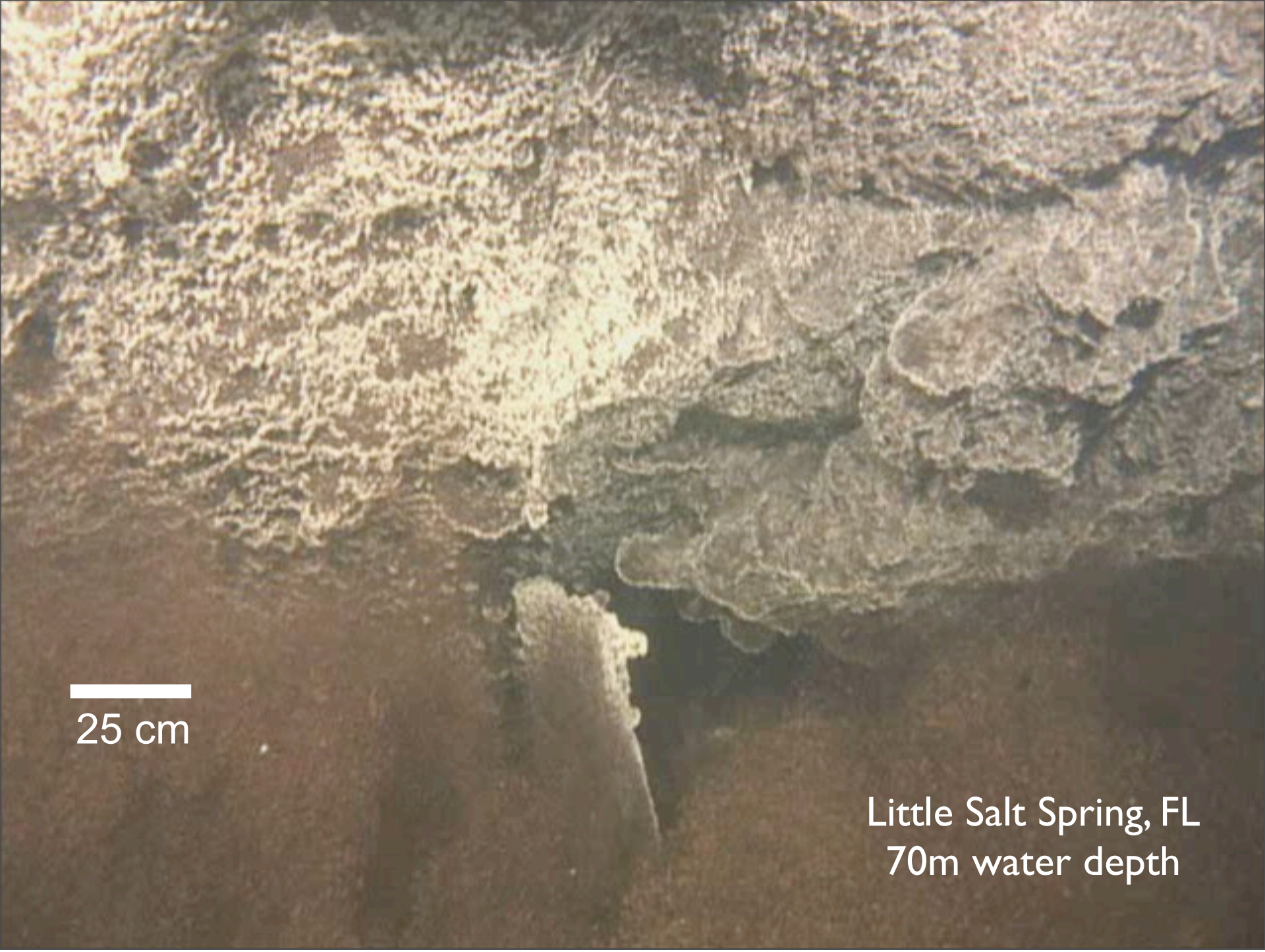
Photo credits S. Mariani

caves (porosity accessible to humans) represent a tiny fraction of porosity created by similar processes

Frasassi Cave System, Italy


1 m
Manantial del Toro,
Dominican Republic
Photo credit DRSS

Manantial del Toro,
Dominican Republic


25 cm
Little Salt Spring, FL
70m water depth

Magical Blue Hole, The Bahamas

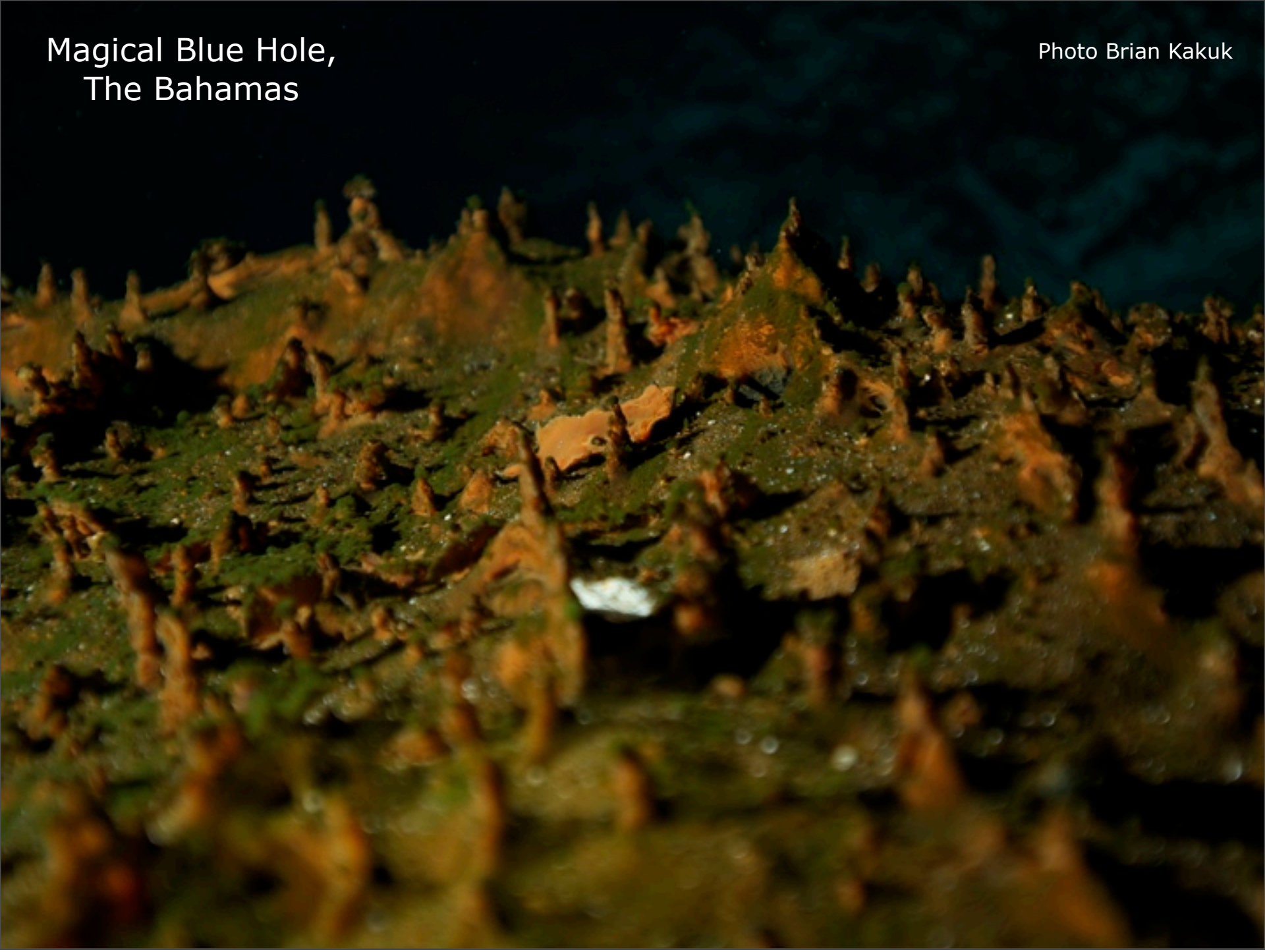
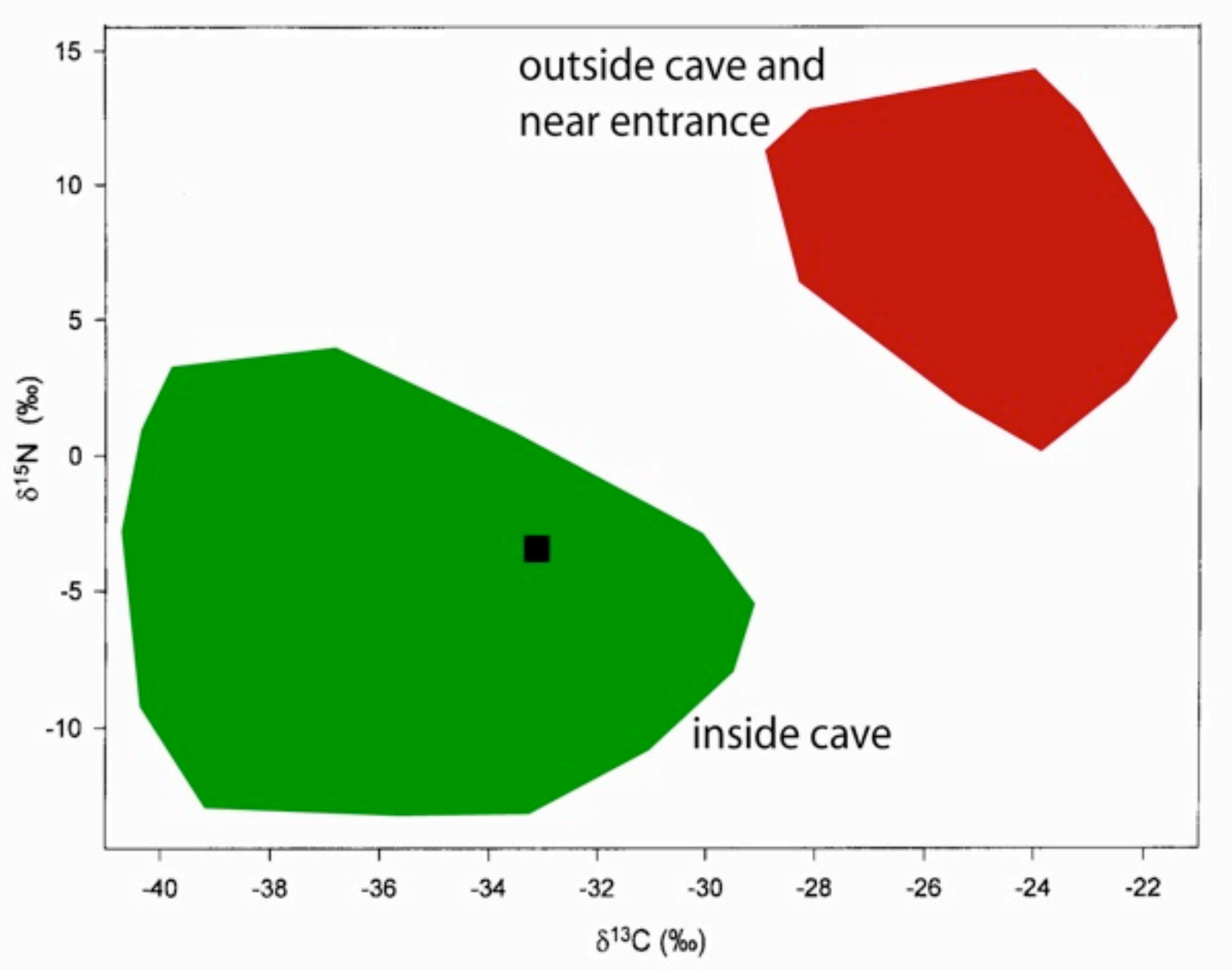
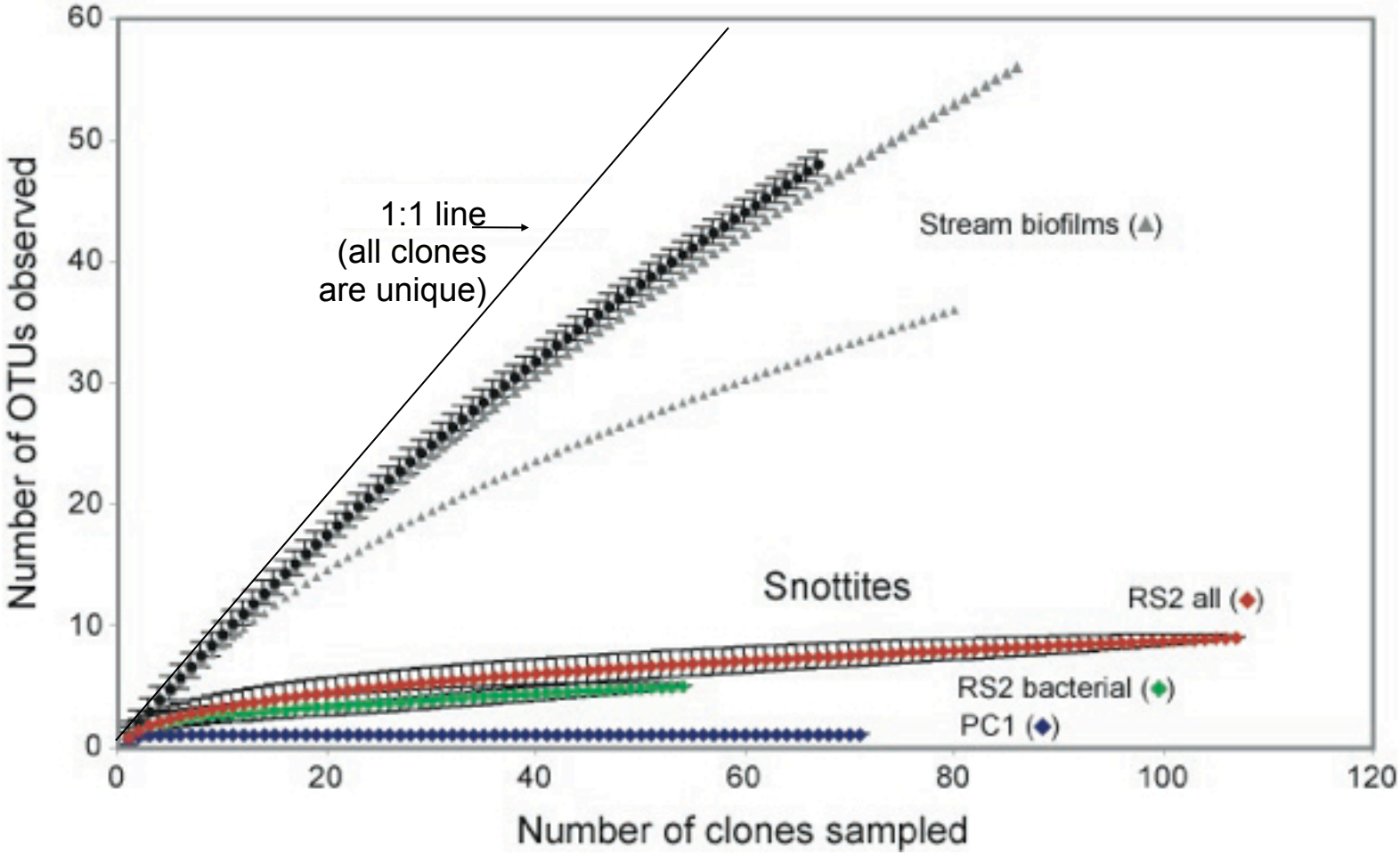


Photo Brian Kakuk

^{13}C and ^{15}N ratios of organic matter

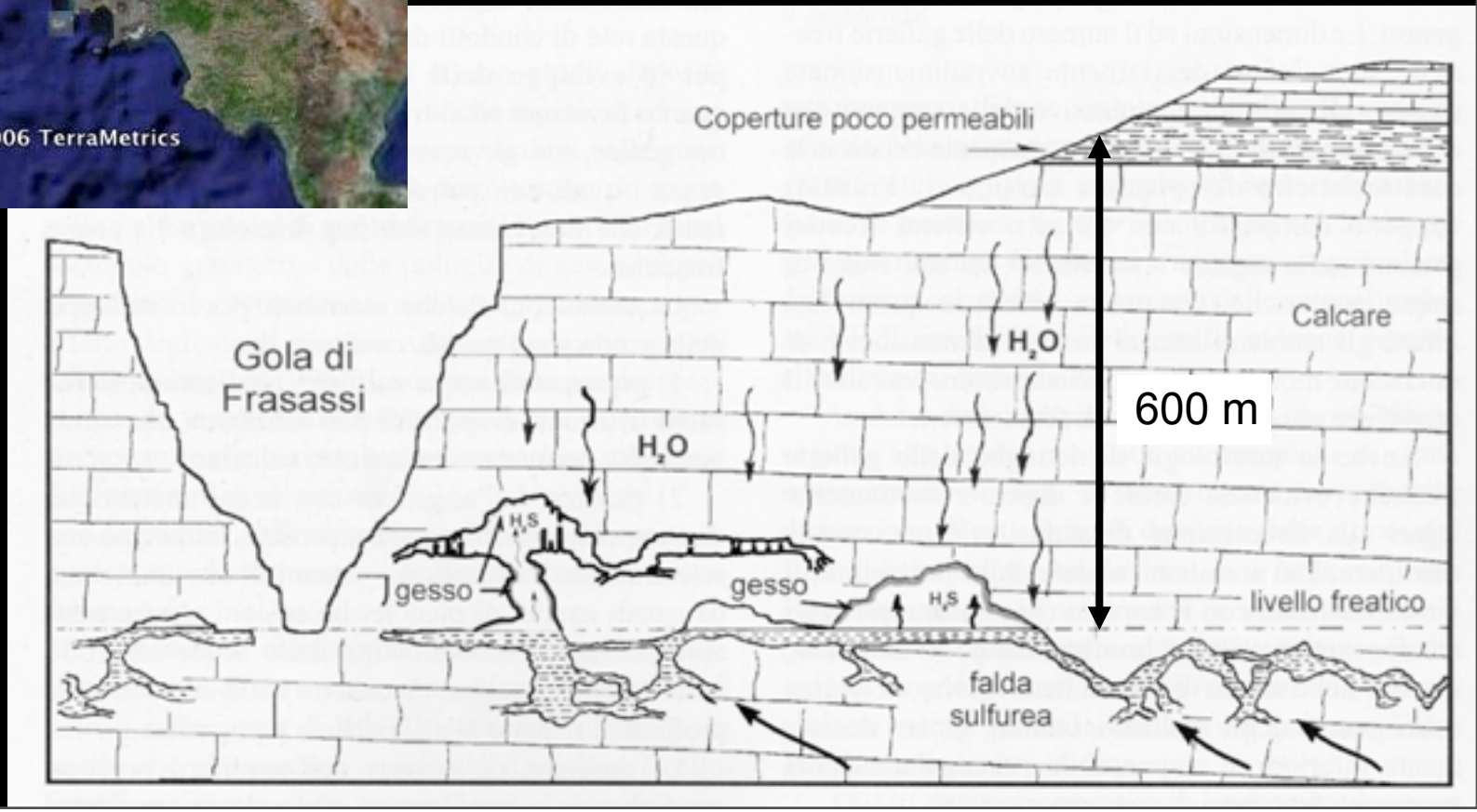


Diversity of 16S rRNA genotypes



OTU (Operational Taxonomic Unit) = 98% sequence similarity

Frasassi Cave System, Italy

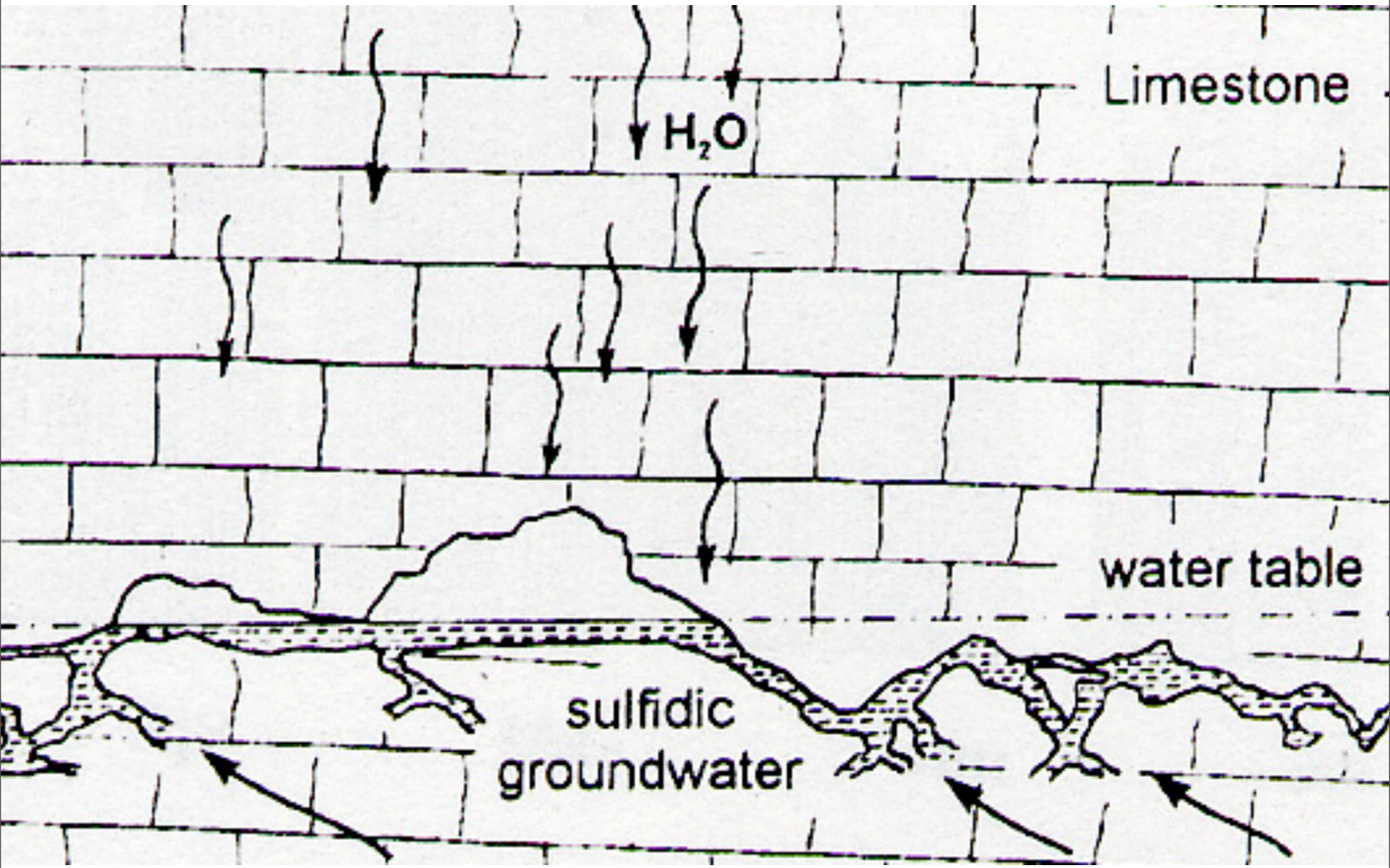


Daniel Jones

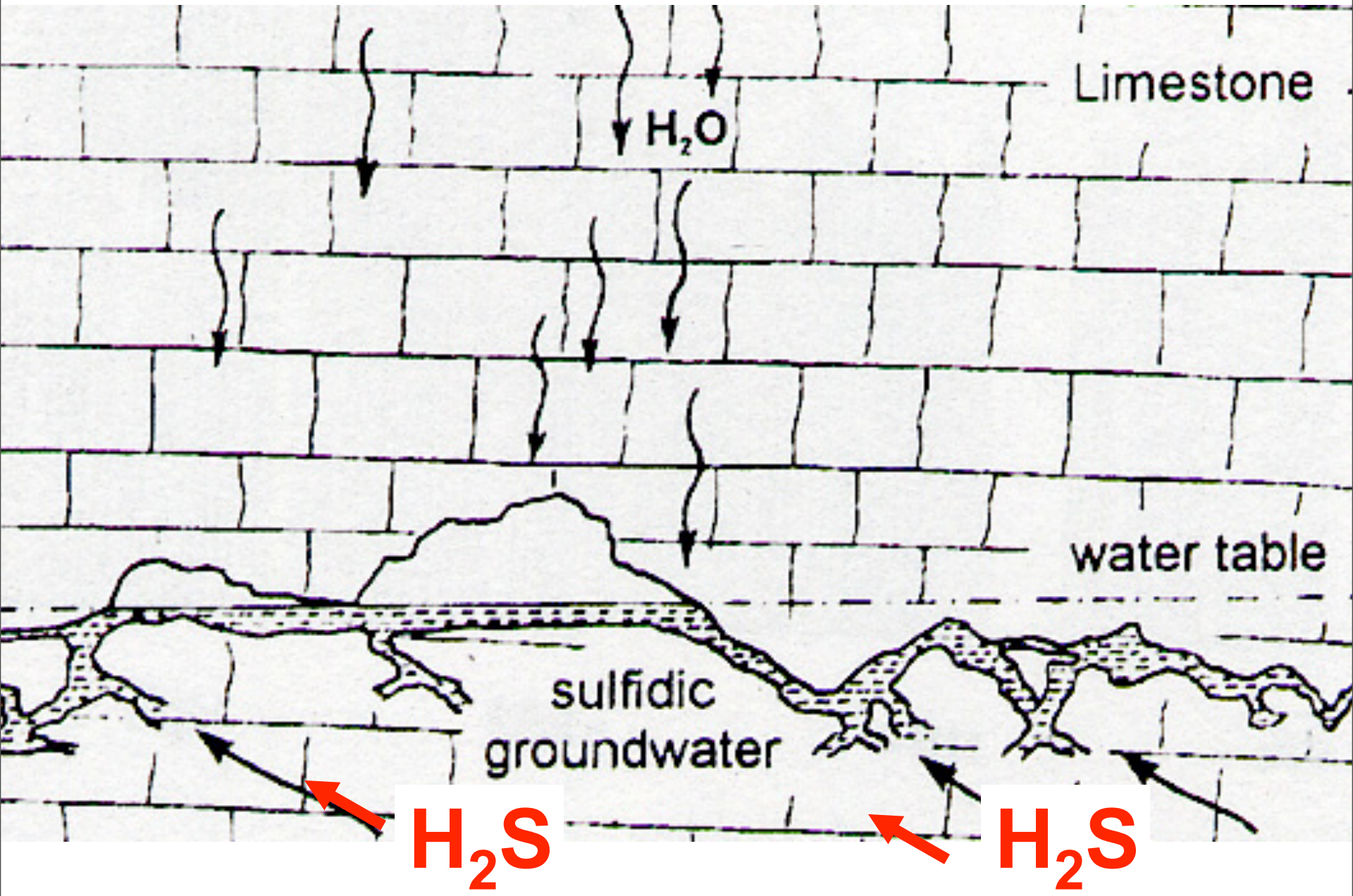
Sharmishtha Dattagupta

Lubos Polerecky
(MPI Bremen)

Rebecca McCauley



Modified from Sarbu et al., 2000



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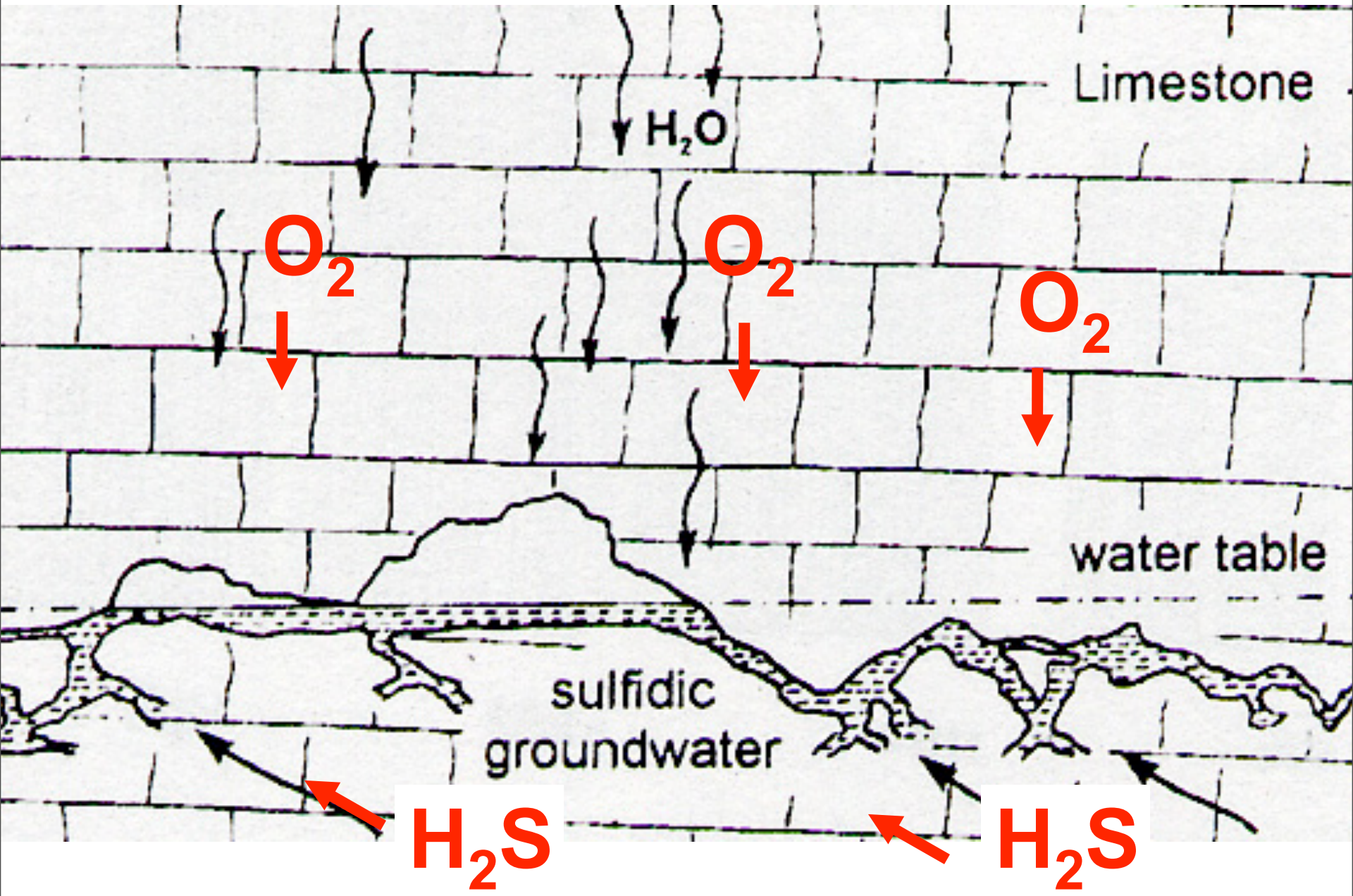

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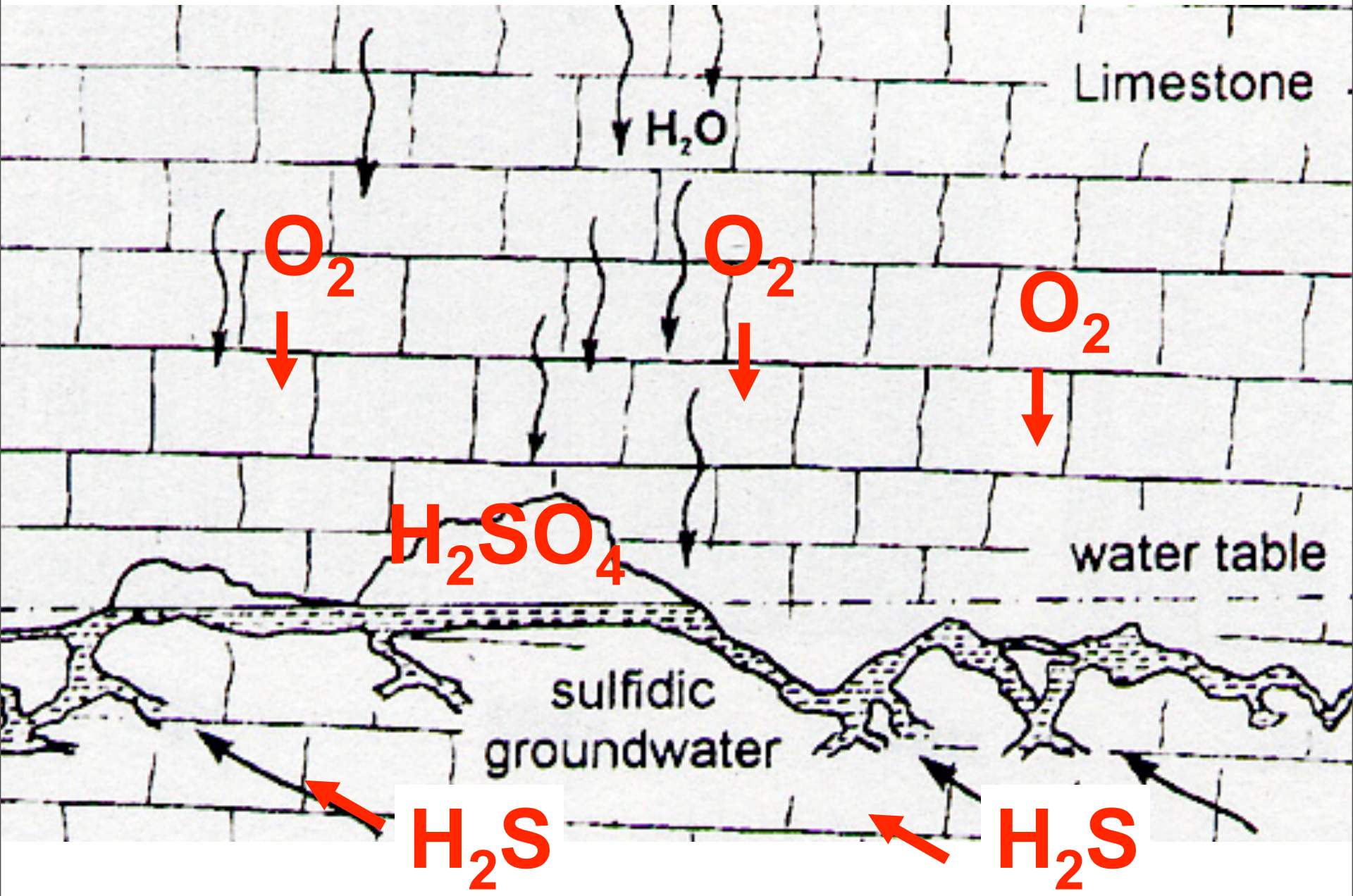

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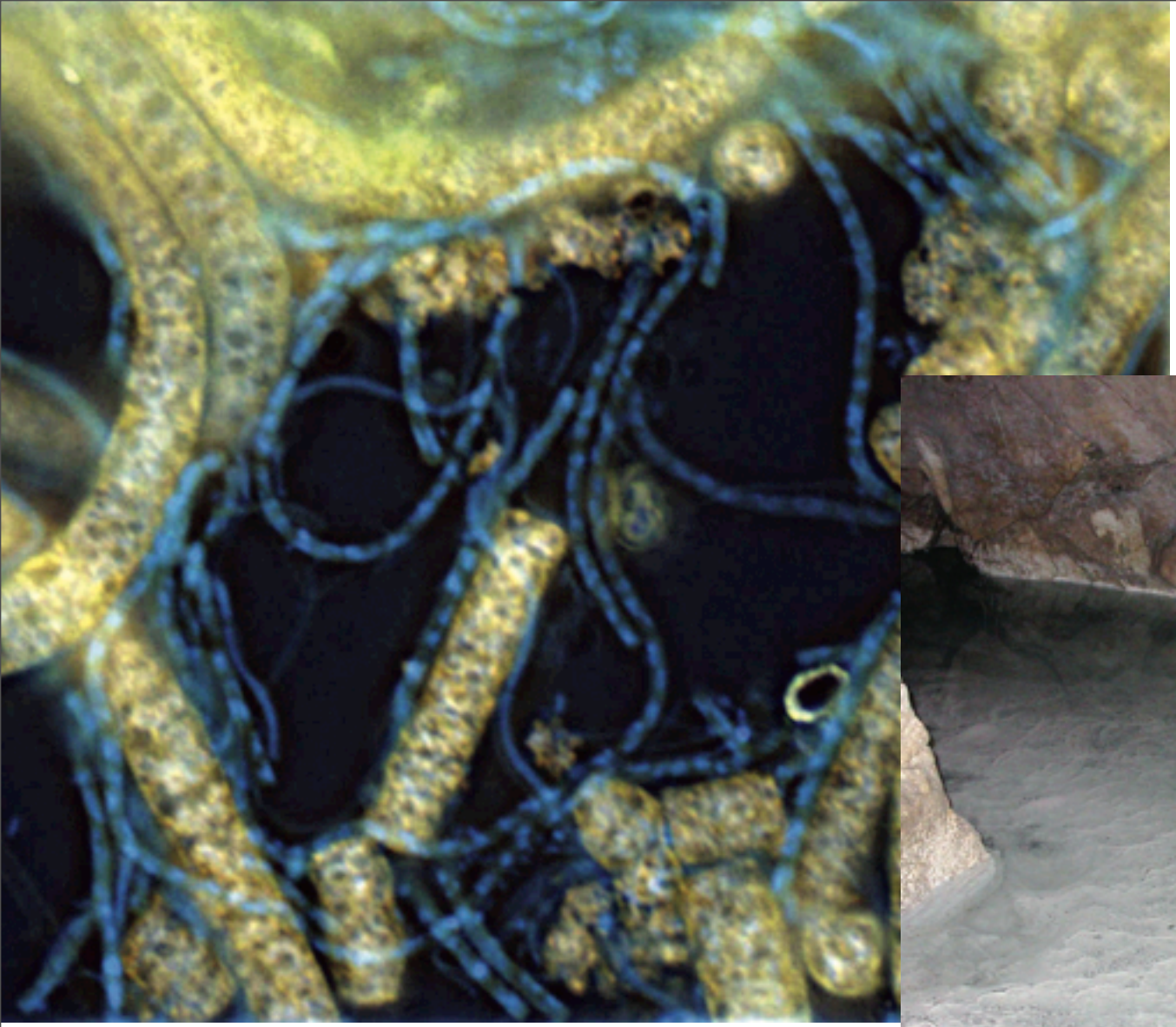
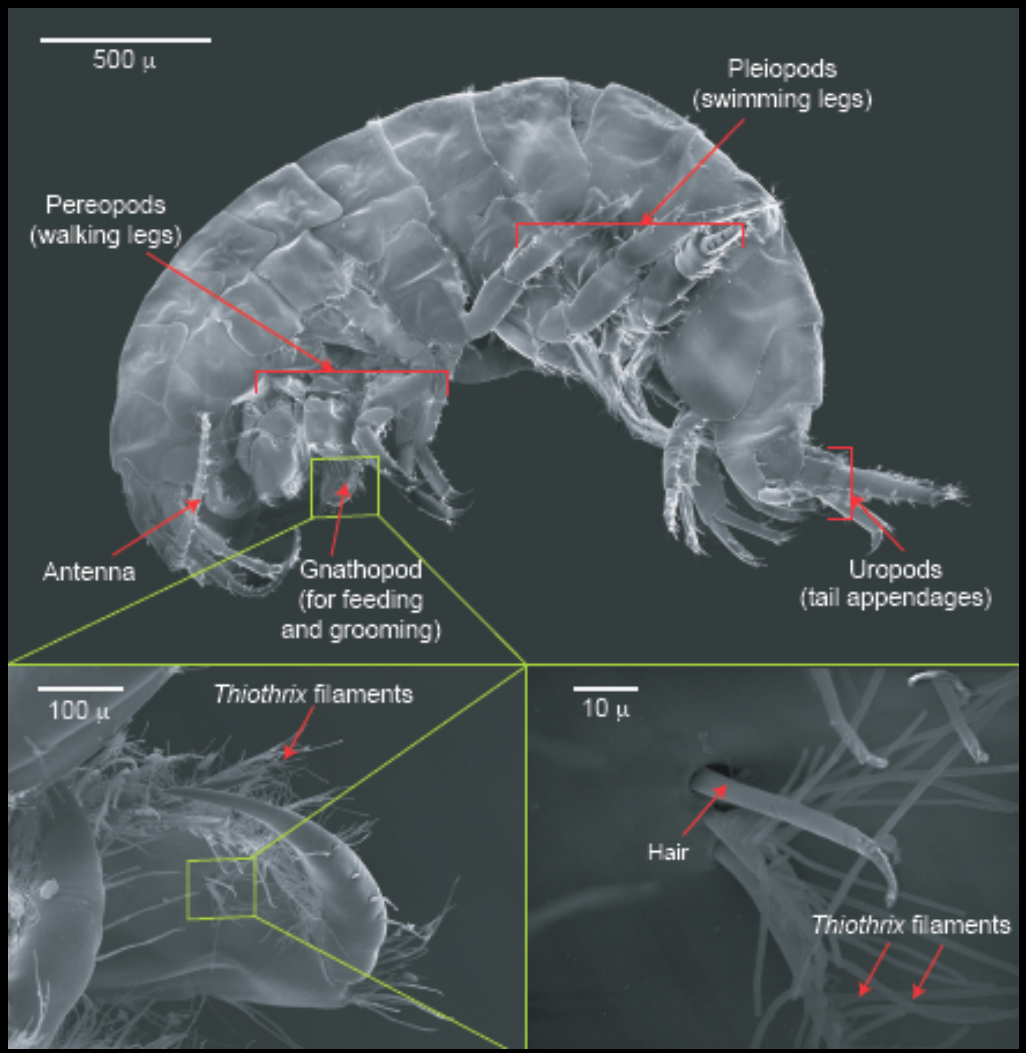
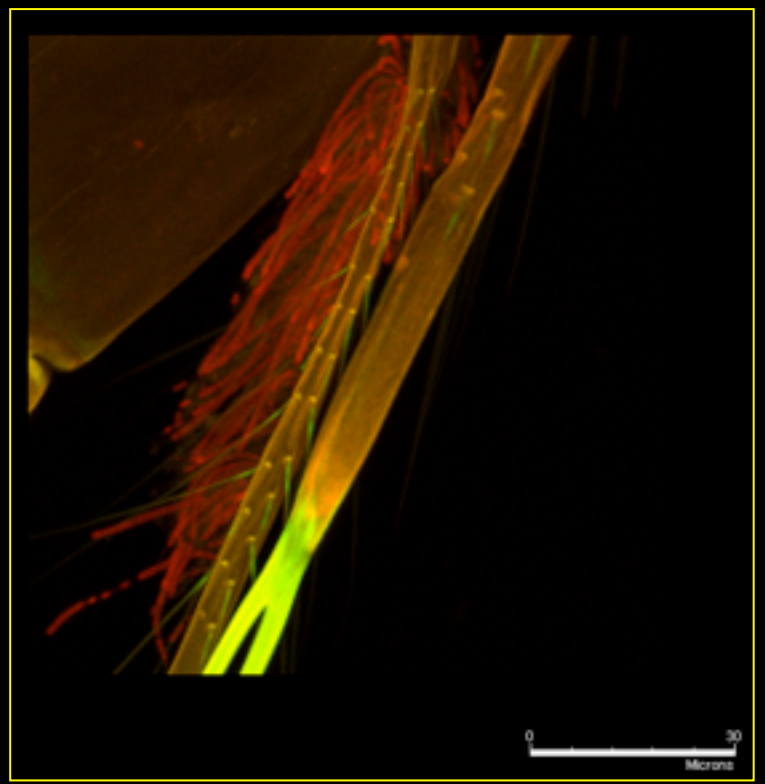


Macalady *et al.* 2006 AEM 72: 5596

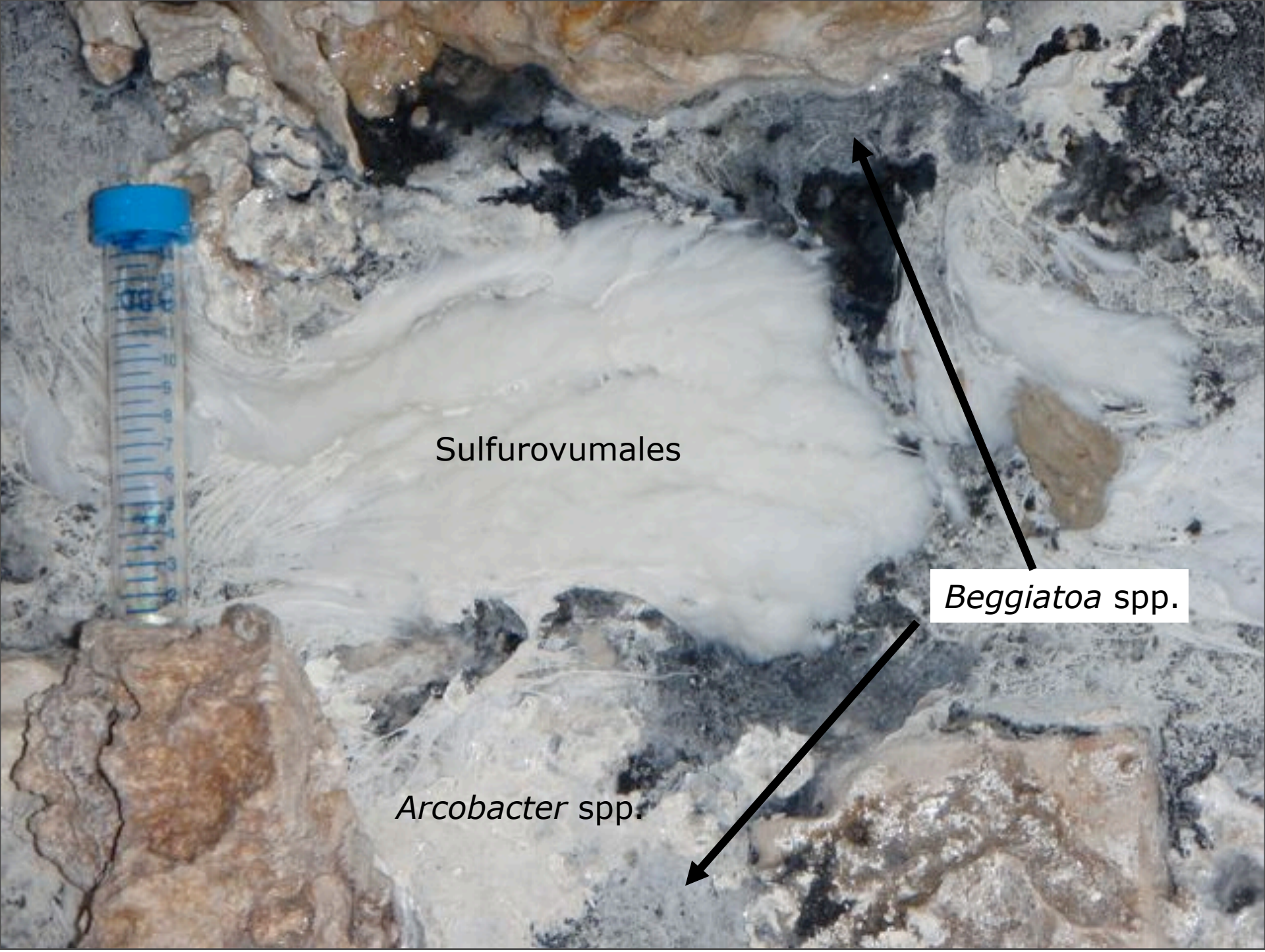
A Recently Evolved Symbiosis Between Chemoautotrophic Bacteria and a Cave-dwelling Amphipod



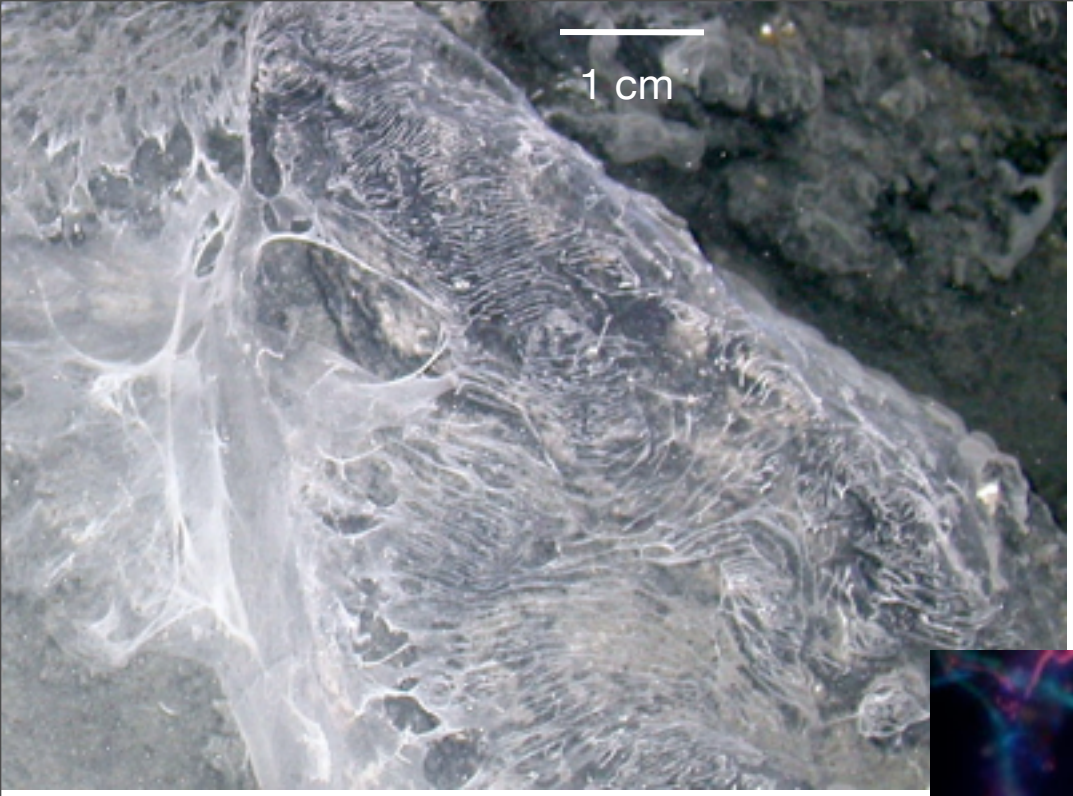


Dattagupta *et al.* 2009 ISMEJ


Microbial Niche
Differentiation

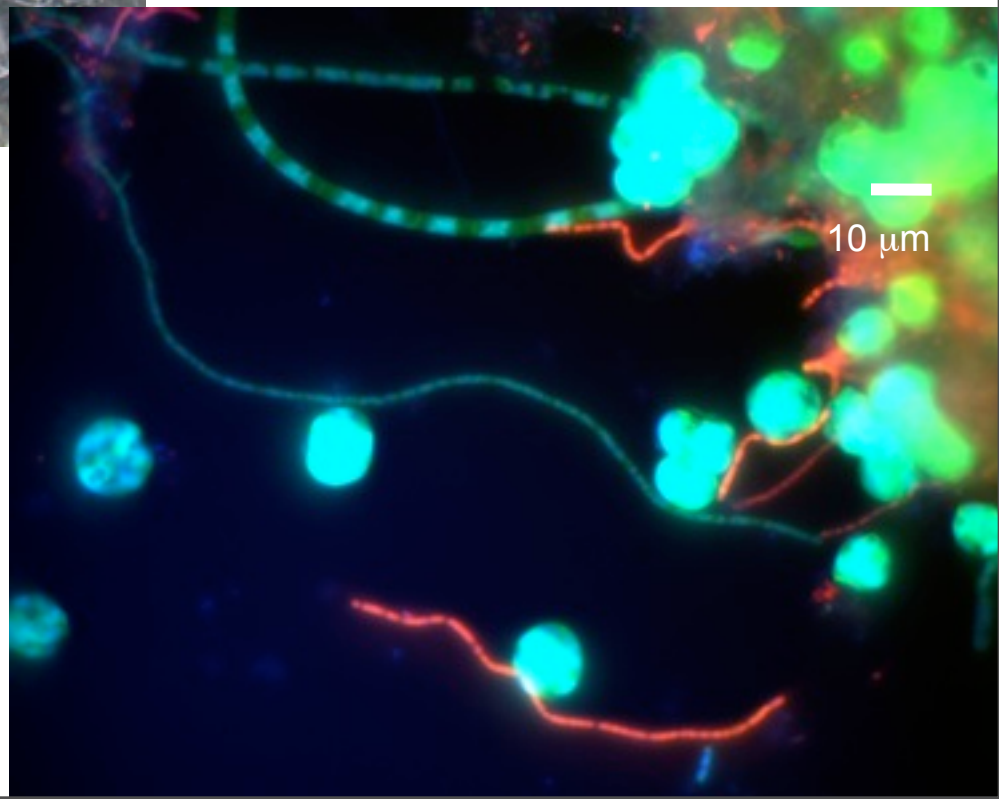

Sulfurovumales
Beggiatoa spp.
Arcobacter spp.

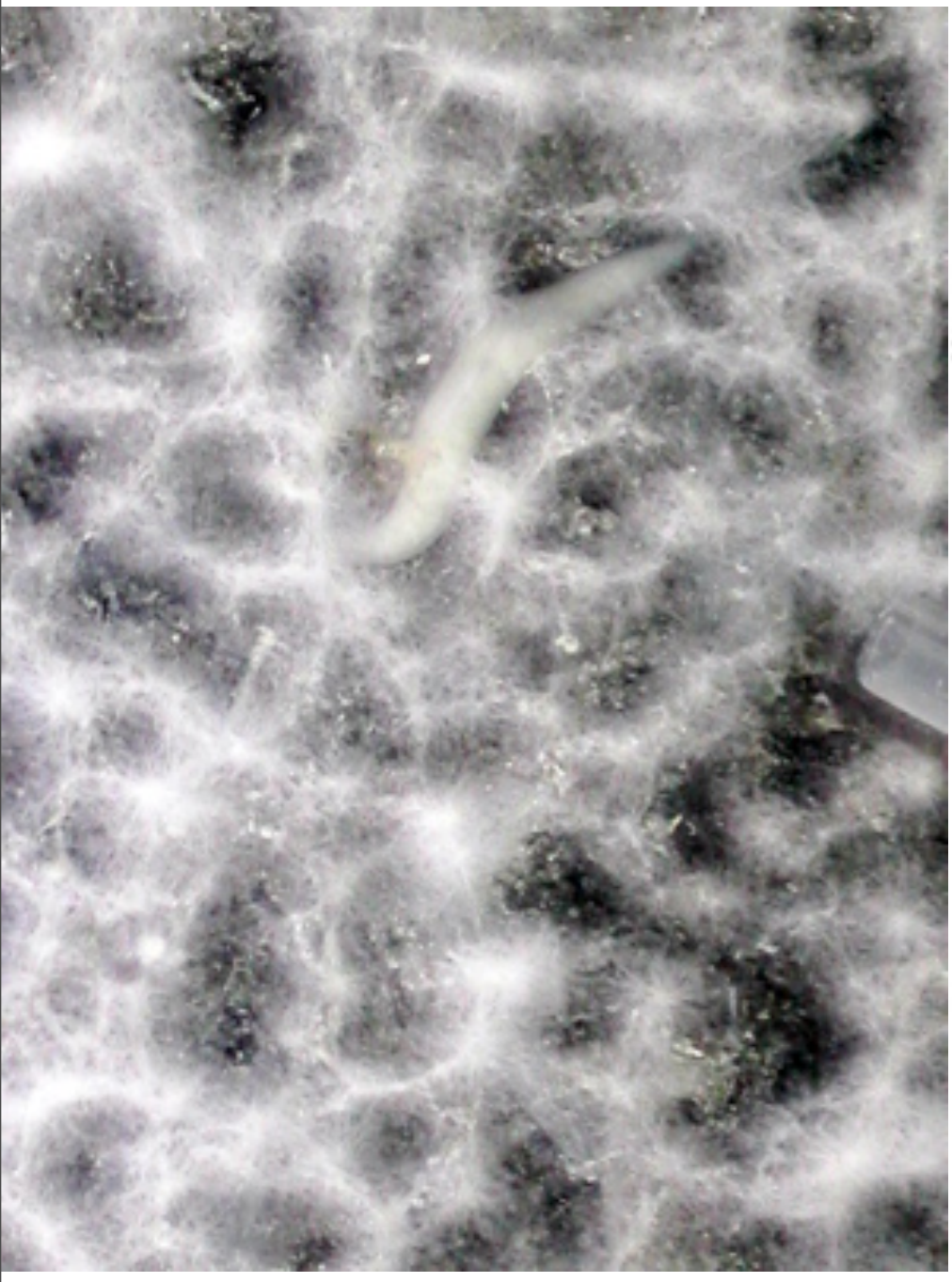
Full cycle rRNA approach



Fluorescent *in situ* hybridization (FISH)

16S rRNA cloning





DELTA495A, THIOBEG806

GAM42A, EUBMIX

GS04-15

RS03-46

A

C

B

D

E

G

F

H

Niche Differentiation

Niche:
The limits, for all important environmental features, within which individuals of a species can survive, grow and reproduce.
(Begon, Harper & Townsend, Ecology, 2nd ed.)

Niche differentiation
(niche segregation, niche separation, niche partitioning)

The tendency for coexisting species to differ in their niche requirements.
(Begon, Harper & Townsend, Ecology, 2nd ed.)

i.e., co-existence is maintained because of specialization, competition is minimized.

The ISME Journal (2008), 1–12

www.nature.com/ismej

ORIGINAL ARTICLE

Niche differentiation among sulfur-oxidizing bacterial populations in cave waters

Jennifer L Macalady[1], Sharmishtha Dattagupta[1], Irene Schaperdoth[1], Daniel S Jones[1], Greg K Druschel[2] and Danielle Eastman[2]

[1]*Department of Geosciences, Pennsylvania State University, Pennsylvania, PA, USA and* [2]*Department of Geology, University of Vermont, Burlington, VT, USA*

The sulfidic Frasassi cave system affords a unique opportunity to investigate niche relationships among sulfur-oxidizing bacteria, including epsilonproteobacterial clades with no cultivated representatives. Oxygen and sulfide concentrations in the cave waters range over more than two orders of magnitude as a result of seasonally and spatially variable dilution of the sulfidic groundwater. A full-cycle rRNA approach was used to quantify dominant populations in biofilms collected in both diluted and undiluted zones. Sulfide concentration profiles within biofilms were obtained *in situ* using microelectrode voltammetry. Populations in rock-attached streamers depended on the sulfide/oxygen supply ratio of bulk water ($r=0.97$; $P<0.0001$). Filamentous epsilonproteobacteria dominated at high sulfide to oxygen ratios (>150), whereas *Thiothrix* dominated at low ratios (<75). In contrast, *Beggiatoa* was the dominant group in biofilms at the sediment–water interface regardless of sulfide and oxygen concentrations or supply ratio. Our results highlight the versatility and ecological success of *Beggiatoa* in diffusion-controlled niches,

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"Niche differentiation... is rarely explored in field studies of microorganisms but is one of the processes commonly invoked to explain the enormous complexity of natural microbial communities."

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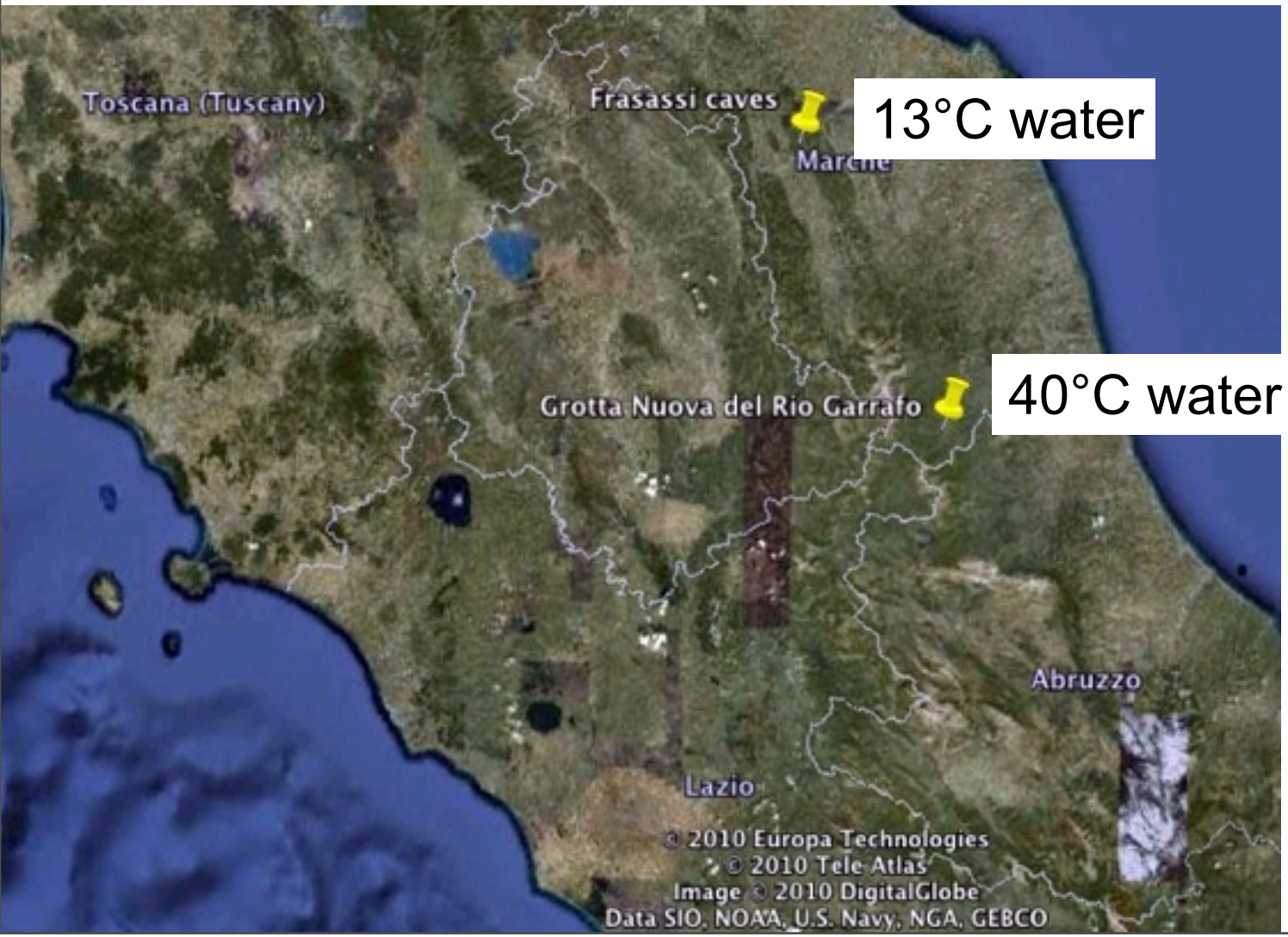
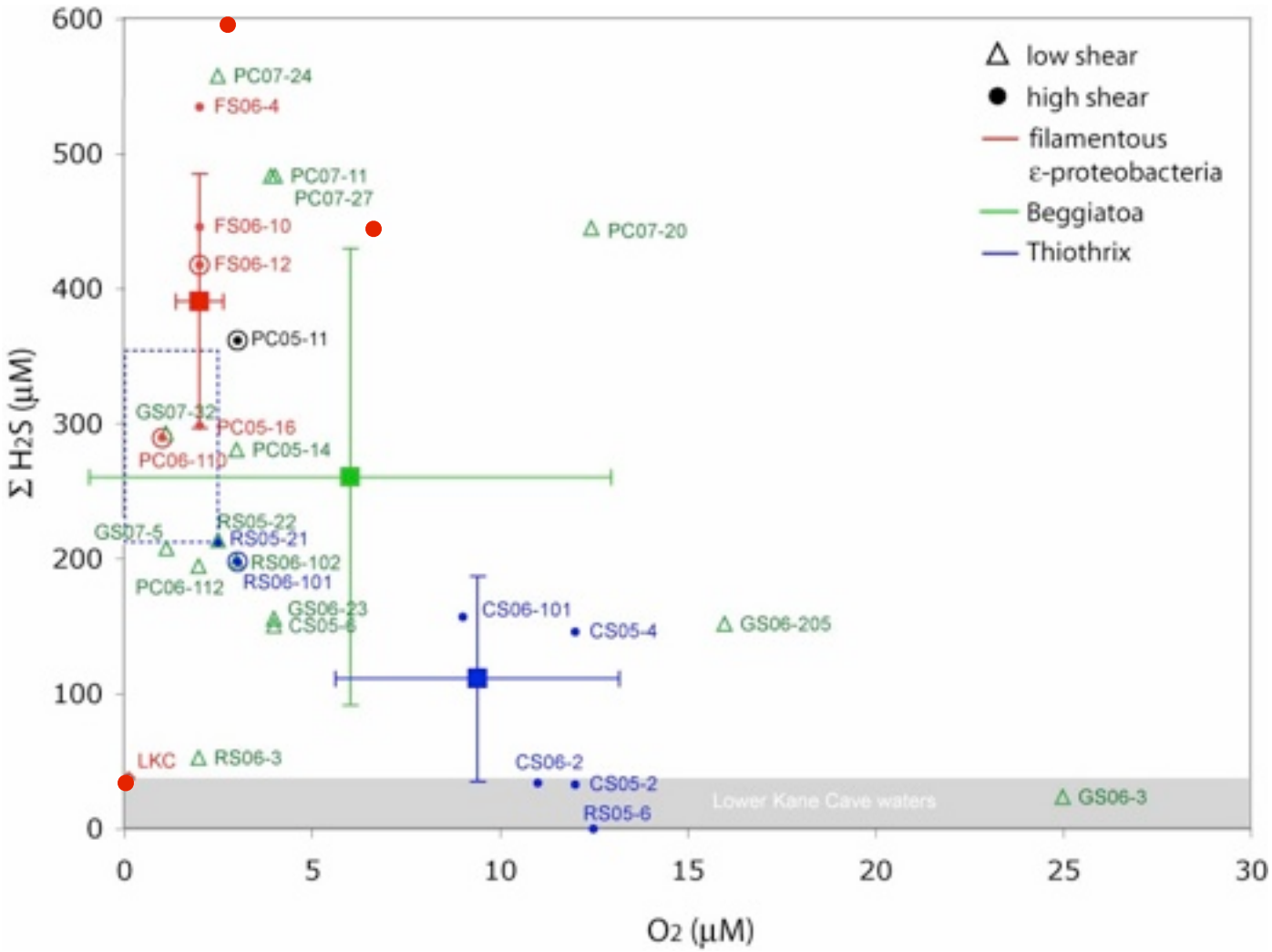
APPLIED AND ENVIRONMENTAL MICROBIOLOGY, Sept. 2010, p. 5902–5910 Vol. 76, No. 17
0099-2240/10/$12.00 doi:10.1128/AEM.00647-10

Community Structure of Subsurface Biofilms in the Thermal Sulfidic Caves of Acquasanta Terme, Italy▽†

D. S. Jones,[1] D. J. Tobler,[1]‡ I. Schaperdoth,[1] M. Mainiero,[2] and J. L. Macalady[1]*



Niche model for aphotic sulfur oxidizers



Macalady *et al.* 2008 ISMEJ

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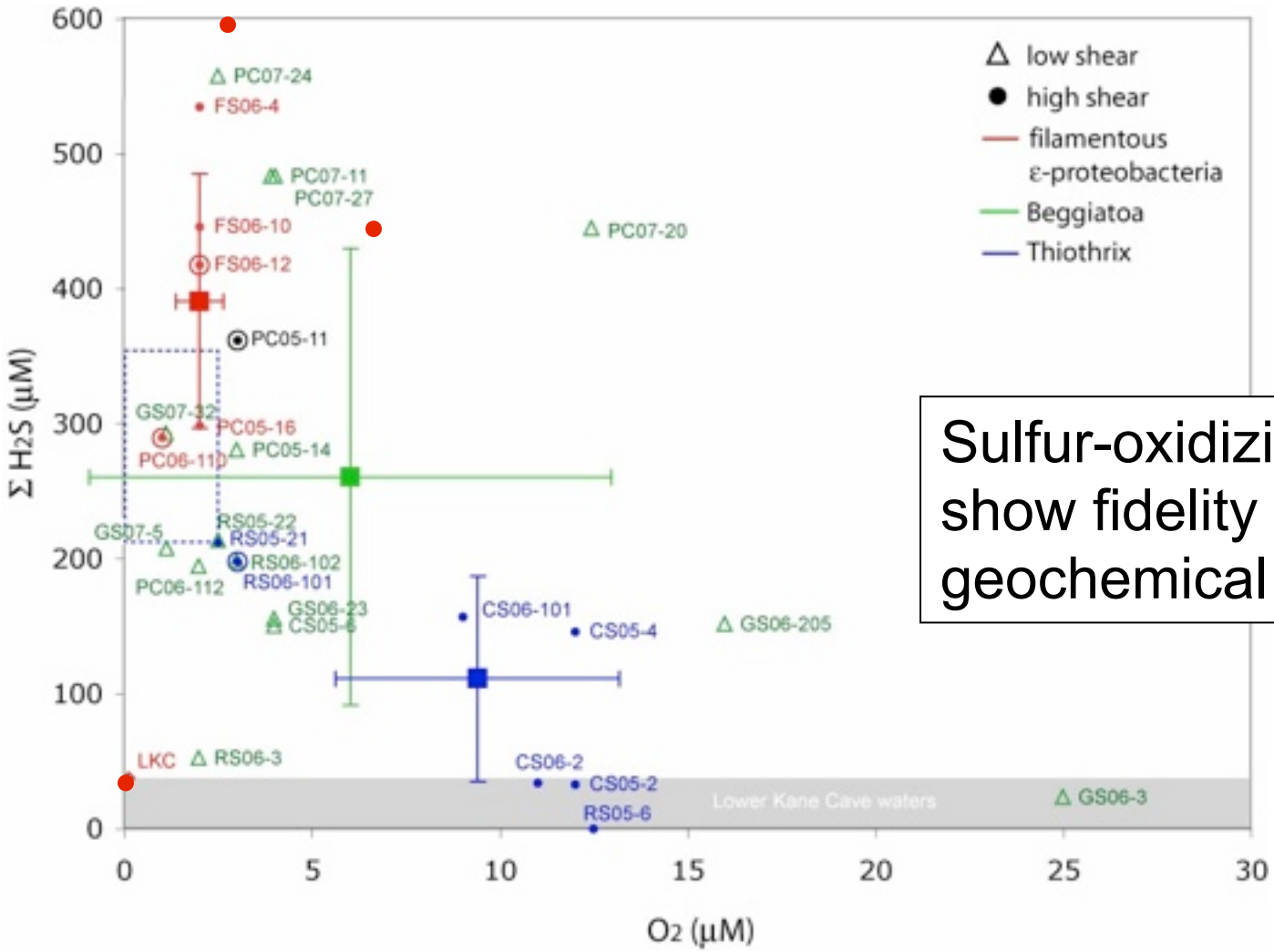
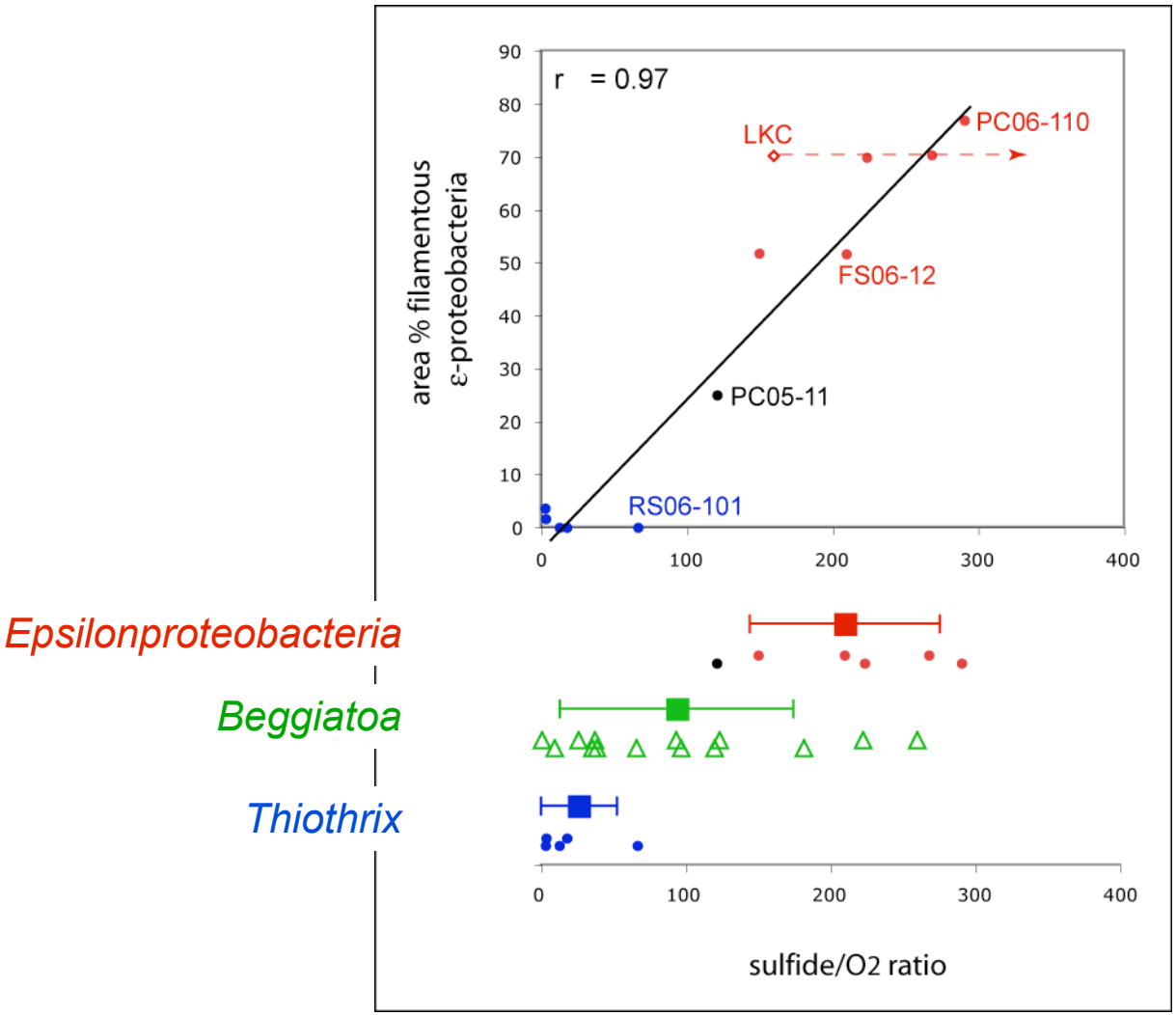


Sulfur-oxidizing clades show fidelity to narrow geochemical niches.

Macalady *et al.* 2008 ISMEJ

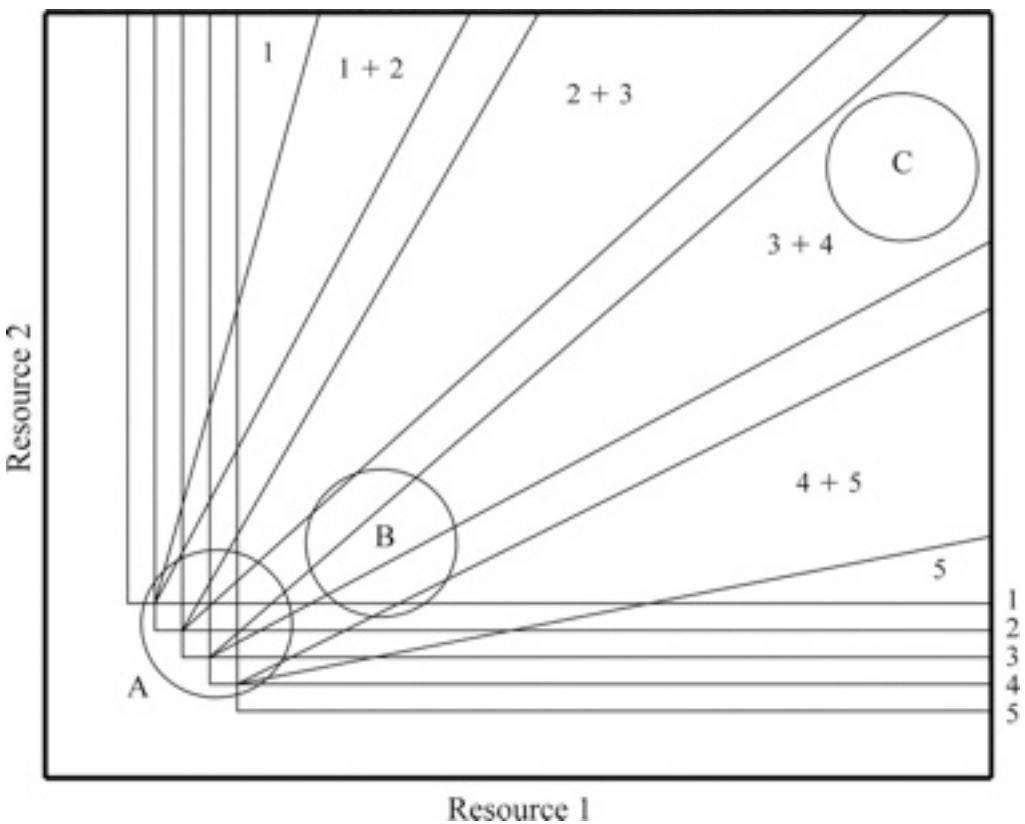
Epsilonproteobacteria biomass correlates with sulfide/oxygen concentration ratio



Macalady *et al.* 2008 ISMEJ

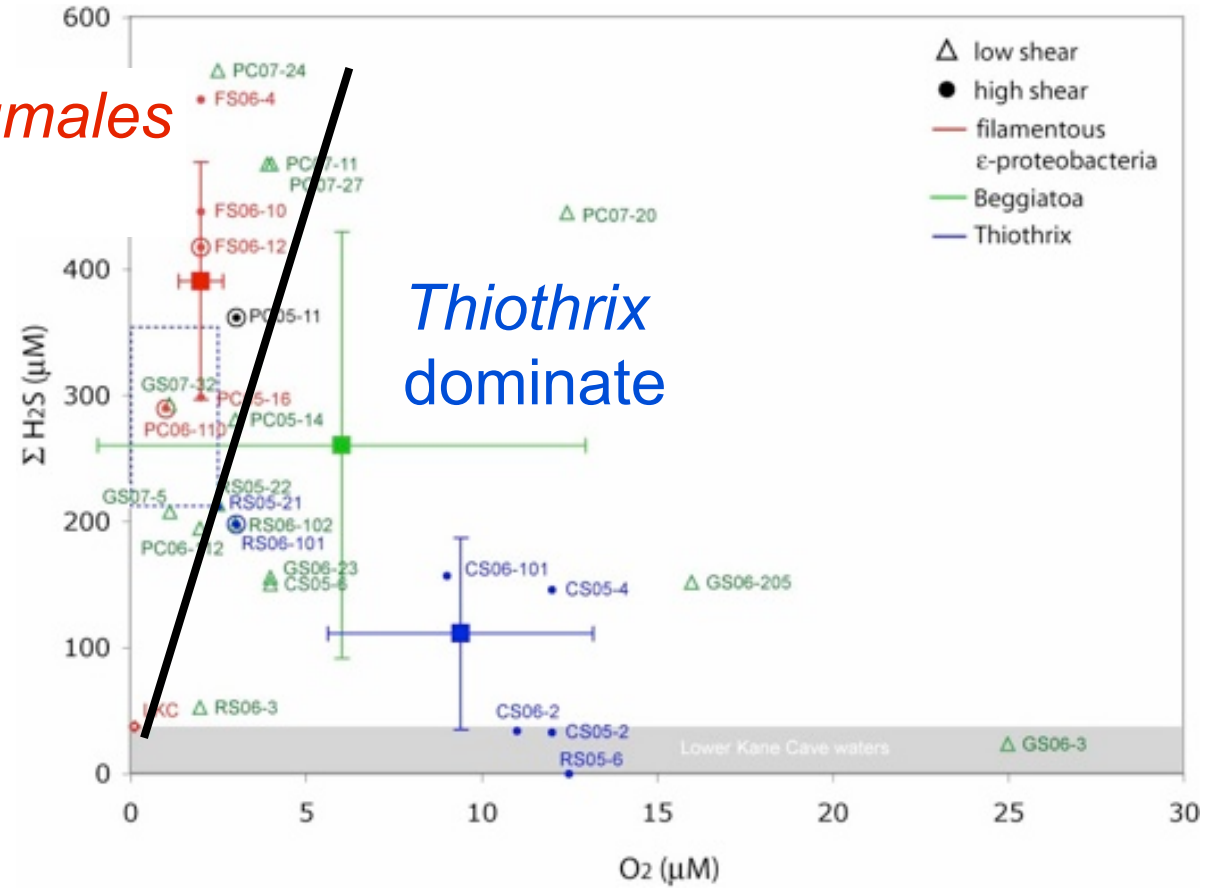
Resource Ratio Theory
Tilman (1980, 1982, 1986)

Prediction:
Species dominance varies with the ratio of the supply rates of resources.

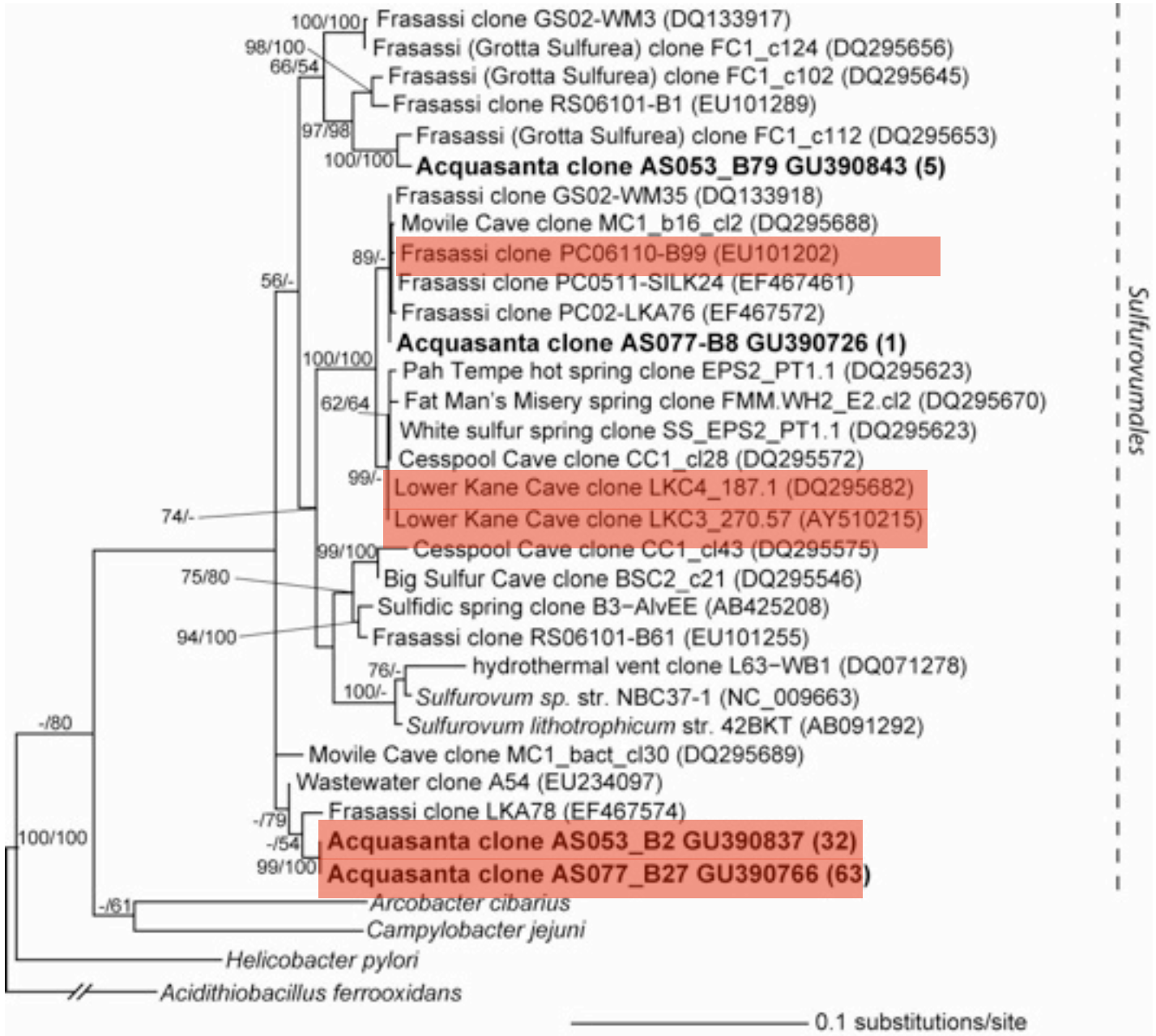


Resource Ratio Theory

Sulfurovumales dominate



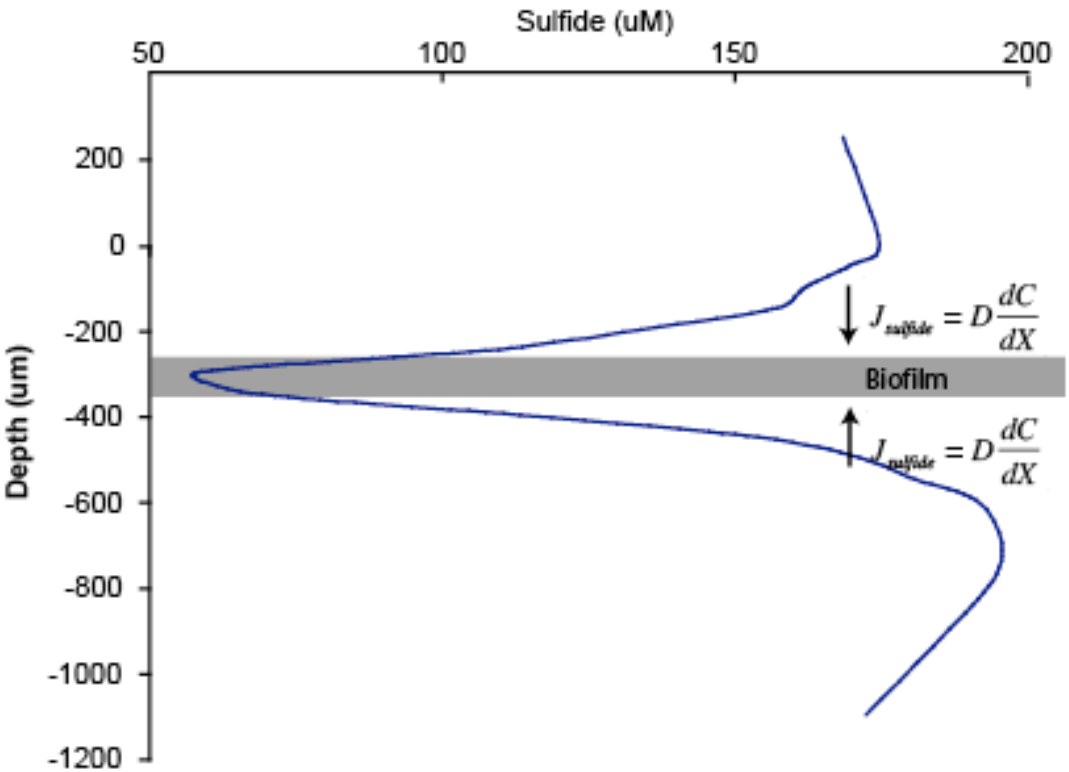
Thiothrix dominate

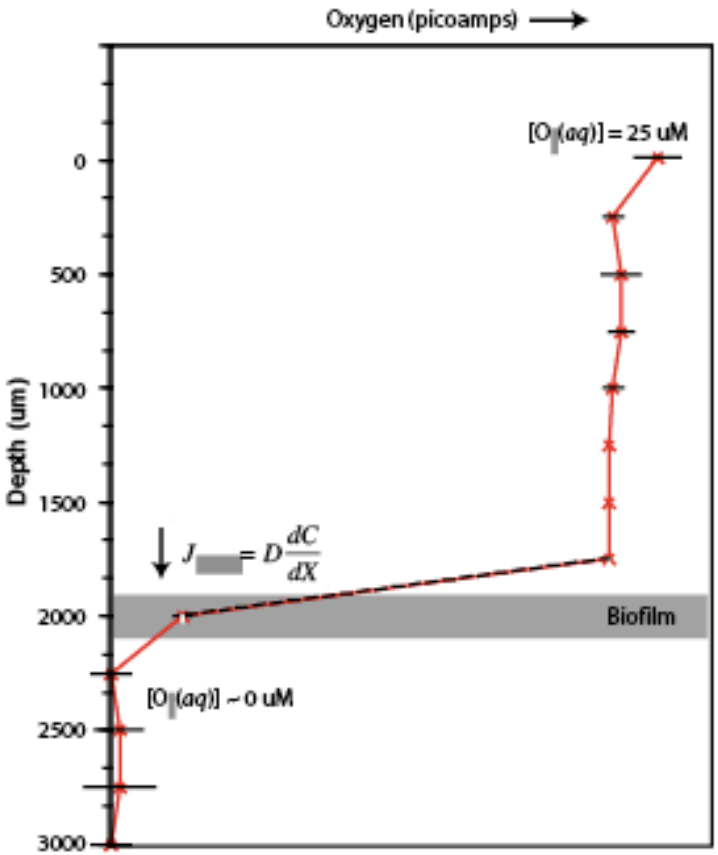

Frasassi clone GS02-WM3 (DQ133917)
Frasassi (Grotta Sulfurea) clone FC1_c124 (DQ295656)
Frasassi (Grotta Sulfurea) clone FC1_c102 (DQ295645)
Frasassi clone RS06101-B1 (EU101289)
Frasassi (Grotta Sulfurea) clone FC1_c112 (DQ295653)
Acquasanta clone AS053_B79 GU390843 (5)
Frasassi clone GS02-WM35 (DQ133918)
Movile Cave clone MC1_b16_cl2 (DQ295688)
Frasassi clone PC06110-B99 (EU101202)
Frasassi clone PC0511-SILK24 (EF467461)
Frasassi clone PC02-LKA76 (EF467572)
Acquasanta clone AS077-B8 GU390726 (1)
Pah Tempe hot spring clone EPS2_PT1.1 (DQ295623)
Fat Man's Misery spring clone FMM.WH2_E2.cl2 (DQ295670)
White sulfur spring clone SS_EPS2_PT1.1 (DQ295623)
Cesspool Cave clone CC1_cl28 (DQ295572)
Lower Kane Cave clone LKC4_187.1 (DQ295682)
Lower Kane Cave clone LKC3_270.57 (AY510215)
Cesspool Cave clone CC1_cl43 (DQ295575)
Big Sulfur Cave clone BSC2_c21 (DQ295546)
Sulfidic spring clone B3−AlvEE (AB425208)
Frasassi clone RS06101-B61 (EU101255)
hydrothermal vent clone L63−WB1 (DQ071278)
Sulfurovum sp. str. NBC37-1 (NC_009663)
Sulfurovum lithotrophicum str. 42BKT (AB091292)
Movile Cave clone MC1_bact_cl30 (DQ295689)
Wastewater clone A54 (EU234097)
Frasassi clone LKA78 (EF467574)
Acquasanta clone AS053_B2 GU390837 (32)
Acquasanta clone AS077_B27 GU390766 (63)
Arcobacter cibarius
Campylobacter jejuni
Helicobacter pylori
Acidithiobacillus ferrooxidans
Sulfurovumales
0.1 substitutions/site

Caver-operated microsensing system (COMS)

Designed by the MPI-Bremen Microsensor Group

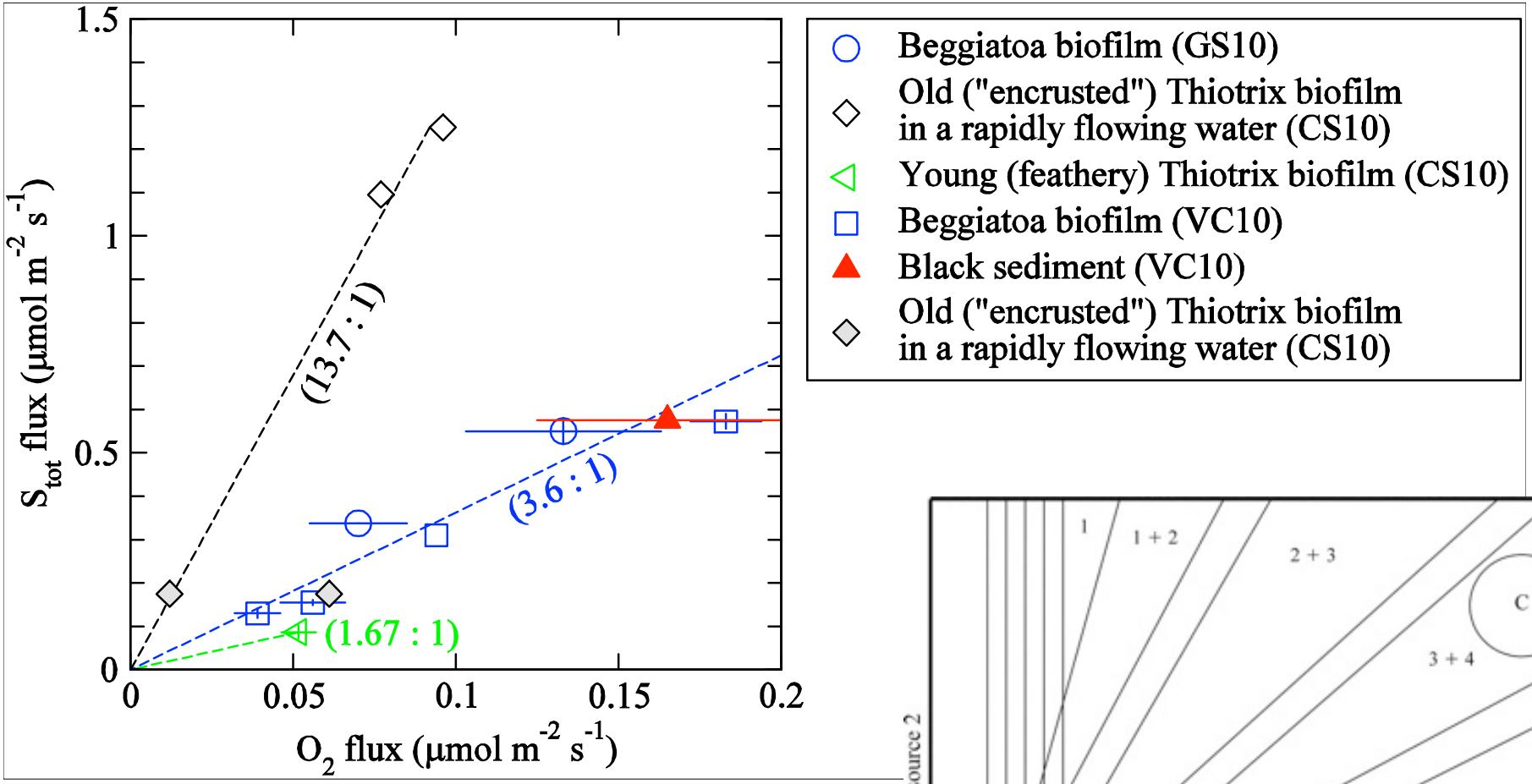
Caver-operated microsensing system (COMS)

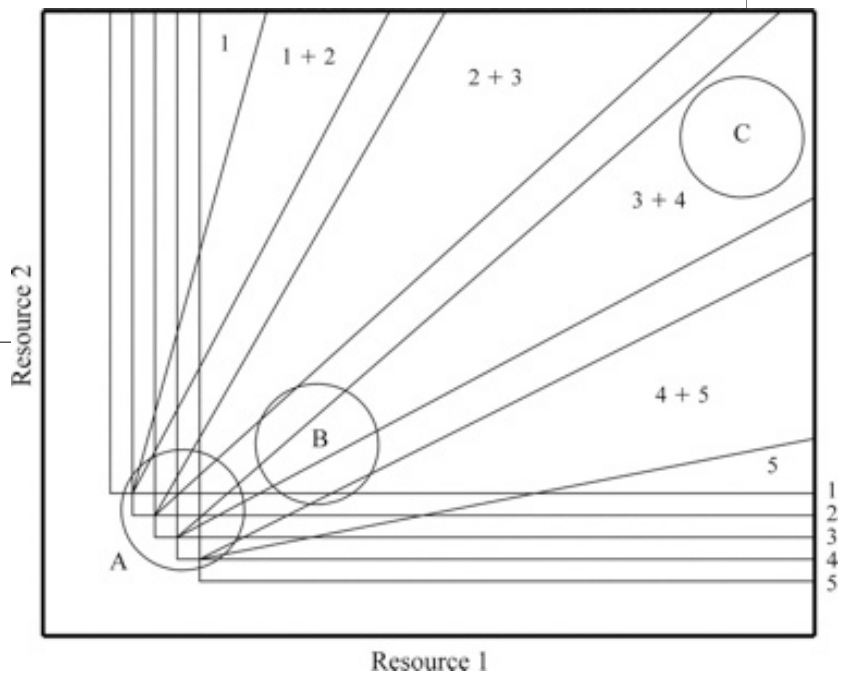




Polerecky *et al.* 2011 in prep.

Caver-operated microsensing system (COMS)





Polerecky *et al.* 2011 in prep.

Microbial Niche Differentiation

1) Globally distributed sulfur-oxidizing clades show fidelity to narrow geochemical niches.

2) Niche separation between these clades occurred in the distant evolutionary past.

3) Preliminary microelectrode data are consistent with predictions from resource ratio theory .

Summary

- caves are windows that allow us to study subsurface biogeochemical processes that occur on a wider scale
- redox interfaces in the terrestrial subsurface are common and associated with isolated lithoautotrophic microbial communities
- because of relatively low chemical and biological complexity, these communities are good model systems

Thanks to:

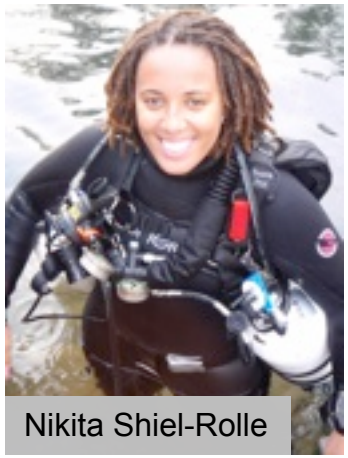
NATIONAL GEOGRAPHIC

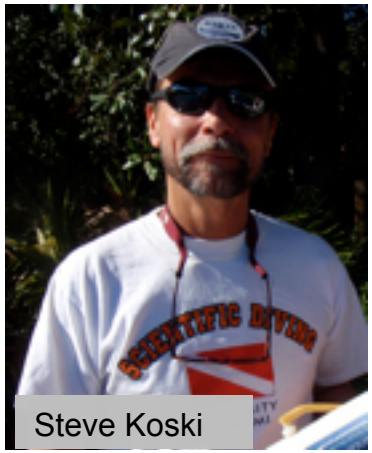
Dominican Republic Speleological Society
Exploration Research Survey

Penn State Science Diving Program


Kenneth Broad


Jill Heinerth


Nikita Shiel-Rolle



Steve Koski


Brian Kakuk

Credit Jill Heinerth

Thanks to:

Alessandro Montanari (Osservatorio Geologico di Coldigioco)
Dirk de Beer (MPI-Bremen)
Greg Druschel (Univ. of Vermont)
Sandro Galdenzi
Simone Cerioni
Sandro Mariani
Maurizio Mainiero