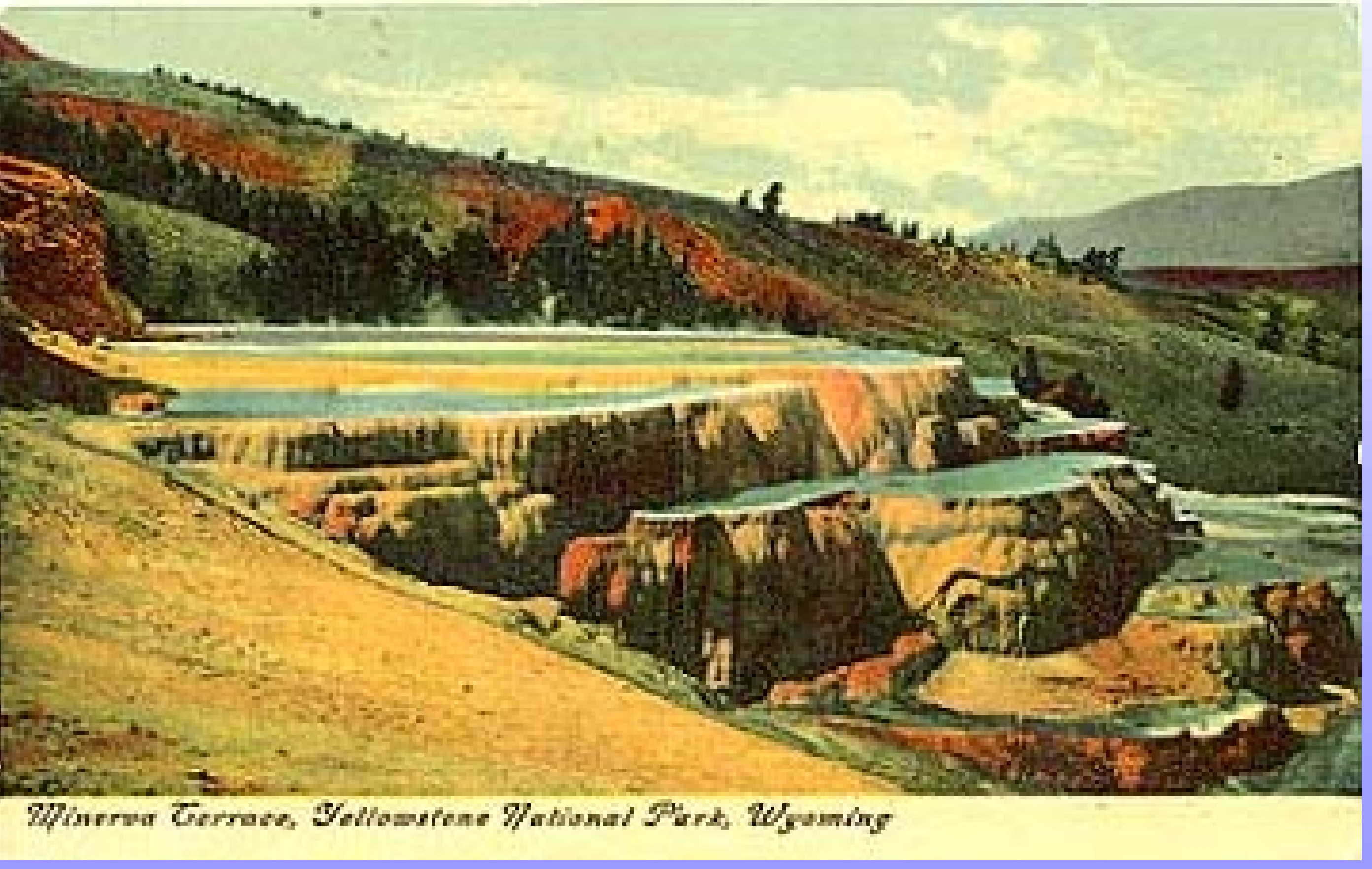
Geobiological Pattern Formation at Yellowstone's Hot Springs



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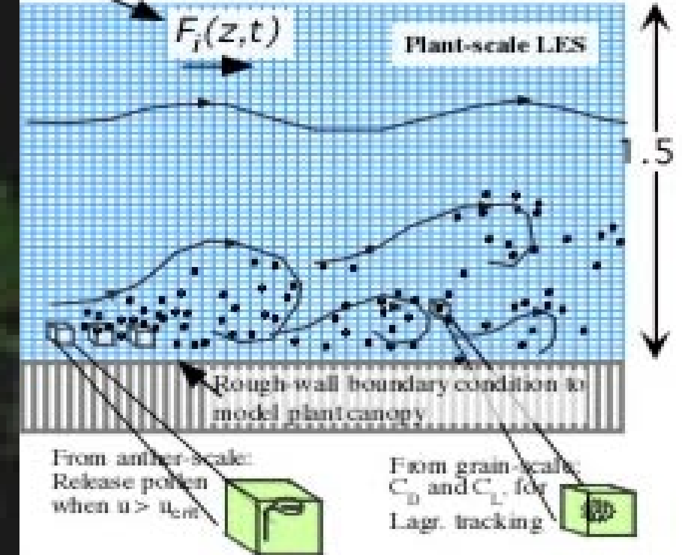
Outline

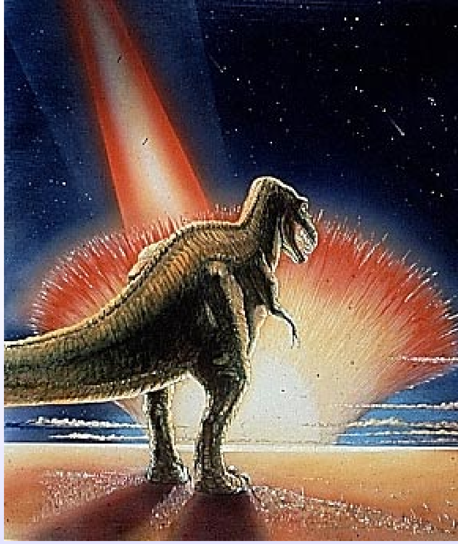
- **What is Geobiology?**
  - Biocomplexity - and what physicists can contribute
- **A virtual tour of Yellowstone’s hot springs**
  - Facies concept
- **Possible role of microbes in pattern formation**
  - Biotic vs. abiotic formation
- **Microbial ecology: microbes track facies!**
- **Laboratory work at Illinois**
  - Stromatolites
  - Modelling






Biocomplexity

Biocomplexity



- **What is "complexity"?**
  - Complexity = structure + large fluctuations

- **The big idea: research on the individual components of complex systems provides only limited information about the behavior of the systems themselves**

- **Complexity arising from interplay of biological, physical and even social systems**

What is biocomplexity?

NSF Solicitation 00-22

- "Biocomplexity arises from dynamics spanning several levels within a system, between systems, and/or across multiple spatial (microns to thousands of kilometers) and temporal (nanoseconds to eons) scales.
- This special competition will specifically support Research Projects which directly explore nonlinearities, chaotic behavior, emergent phenomena or feedbacks within and between systems and/or integrate across multiple components or scales of time and space in order to better understand and predict the dynamic behavior of systems."

Who cares?

DIRECTORATE FOR BIOLOGICAL SCIENCES

DIRECTORATE FOR COMPUTER AND INFORMATION SCIENCE AND ENGINEERING

DIRECTORATE FOR ENGINEERING

DIRECTORATE FOR GEOSCIENCES

DIRECTORATE FOR MATHEMATICAL AND PHYSICAL SCIENCES

DIRECTORATE FOR SOCIAL, BEHAVIORAL AND ECONOMIC SCIENCES

OFFICE OF POLAR PROGRAMS

Why do they care?

- **Steven Jay Gould, New York Times, Feb 19, 2001**
  - "Homo sapiens possesses between 30,000 and 40,000 genes... In other words, our bodies develop under the directing influence of only half again as many genes as the tiny roundworm ...."
  - "The collapse of the doctrine of one gene for one protein, and one direction of causal flow from basic codes to elaborate totality, marks the failure of reductionism for the complex system that we call biology."
  - "First, the key to complexity is not more genes, but more combinations and interactions generated by fewer units of code — and many of these interactions (as emergent properties, to use the technical jargon) must be explained at the level of their appearance, for they cannot be predicted from the separate underlying parts alone."

Why do they care?

"Major questions about biocomplexity remain unanswered. How does complexity among biological, physical and social systems within the environment arise and change? How do emergent properties develop? How do systems with living components, including those that are human based, respond and adapt to stress? How does information and material move within and across levels in systems? Are adaptation and change predictable? How do humans influence and respond to biocomplexity in natural systems?"

How much do they care?

- **NSF Priority Area. Others are:**
  - Nanoscale Science and Engineering,
  - Information Technology Research,
  - Learning for the 21st Century.
- **Program disbursed $136M over last 3 years.**
- **Examples with physics PIs:**
  - Geobiology and emergence of terraced architecture (UIUC)
  - Gene expression and multicellular organization in Dictyostelium (UCSD, Cornell)
  - Multiscale simulation of avian limb development (Notre Dame)

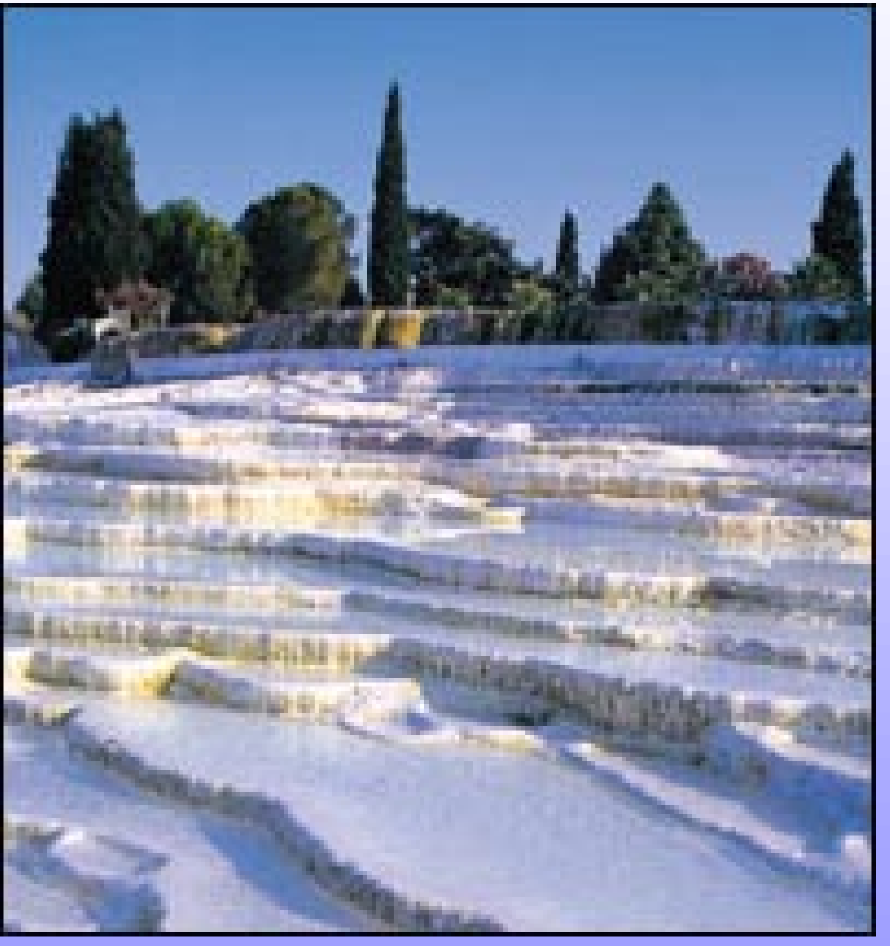
Geobiology

Biocomplexity studies conducted in a geological context that permits results of studies in modern environments to be applied to ancient environments in deep geological time

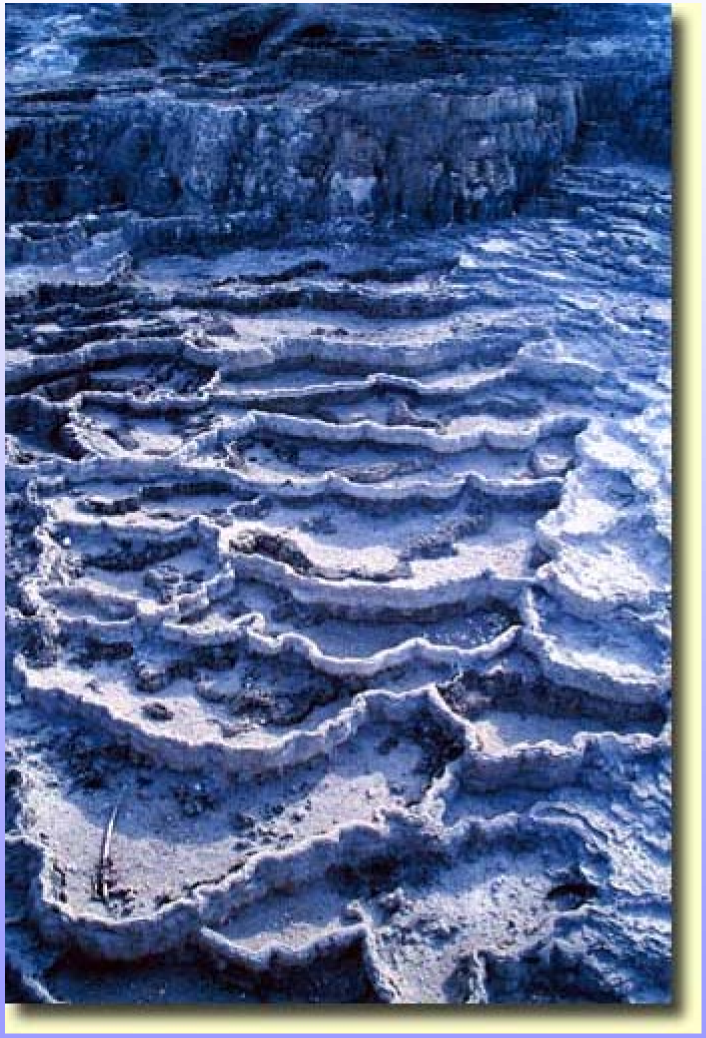
What is the interaction between purely physical geological processes and biological processes?

Travertine terraces at hot springs

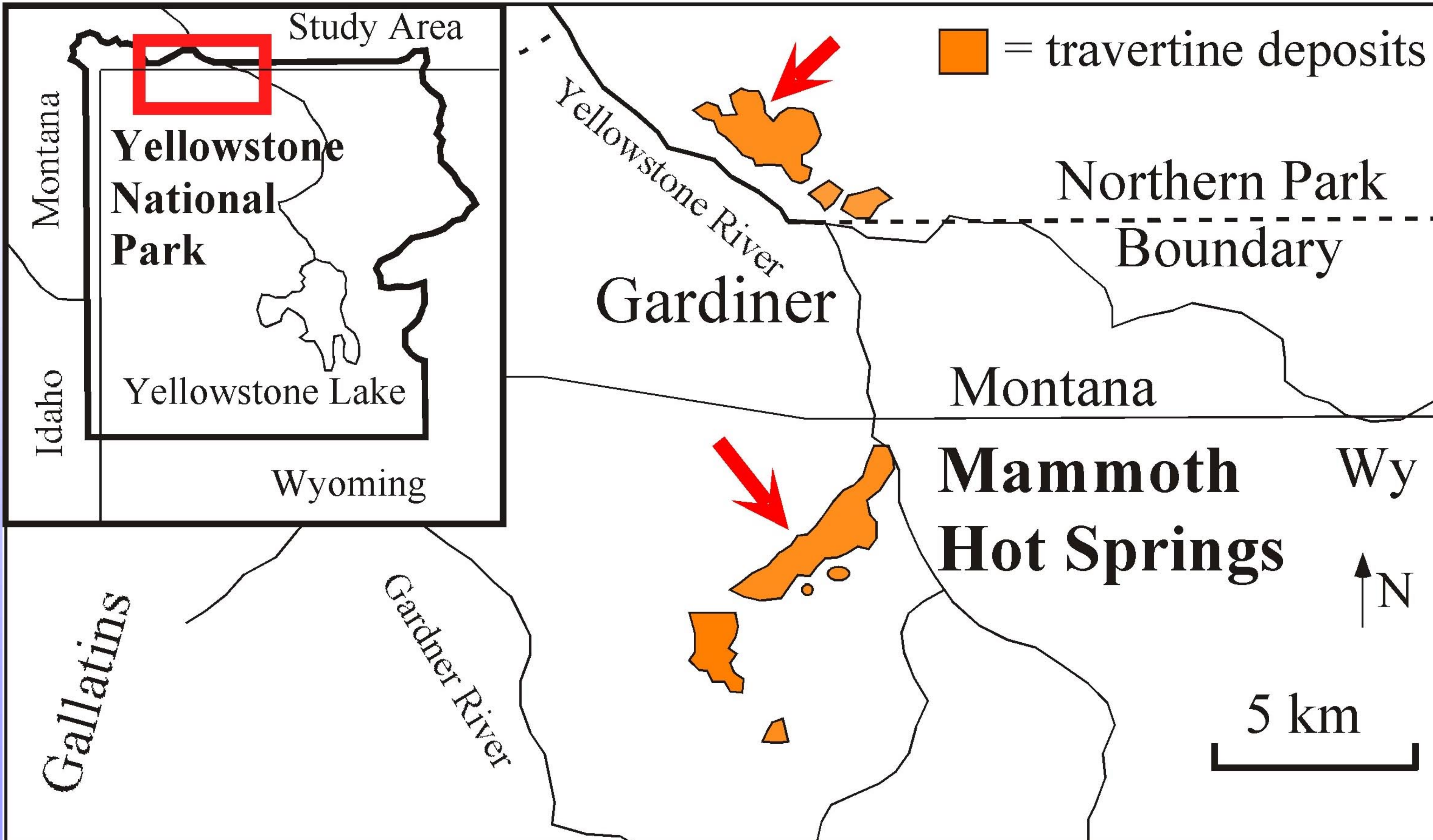
Travertine terraces at hot springs



Travertine terraces at hot springs

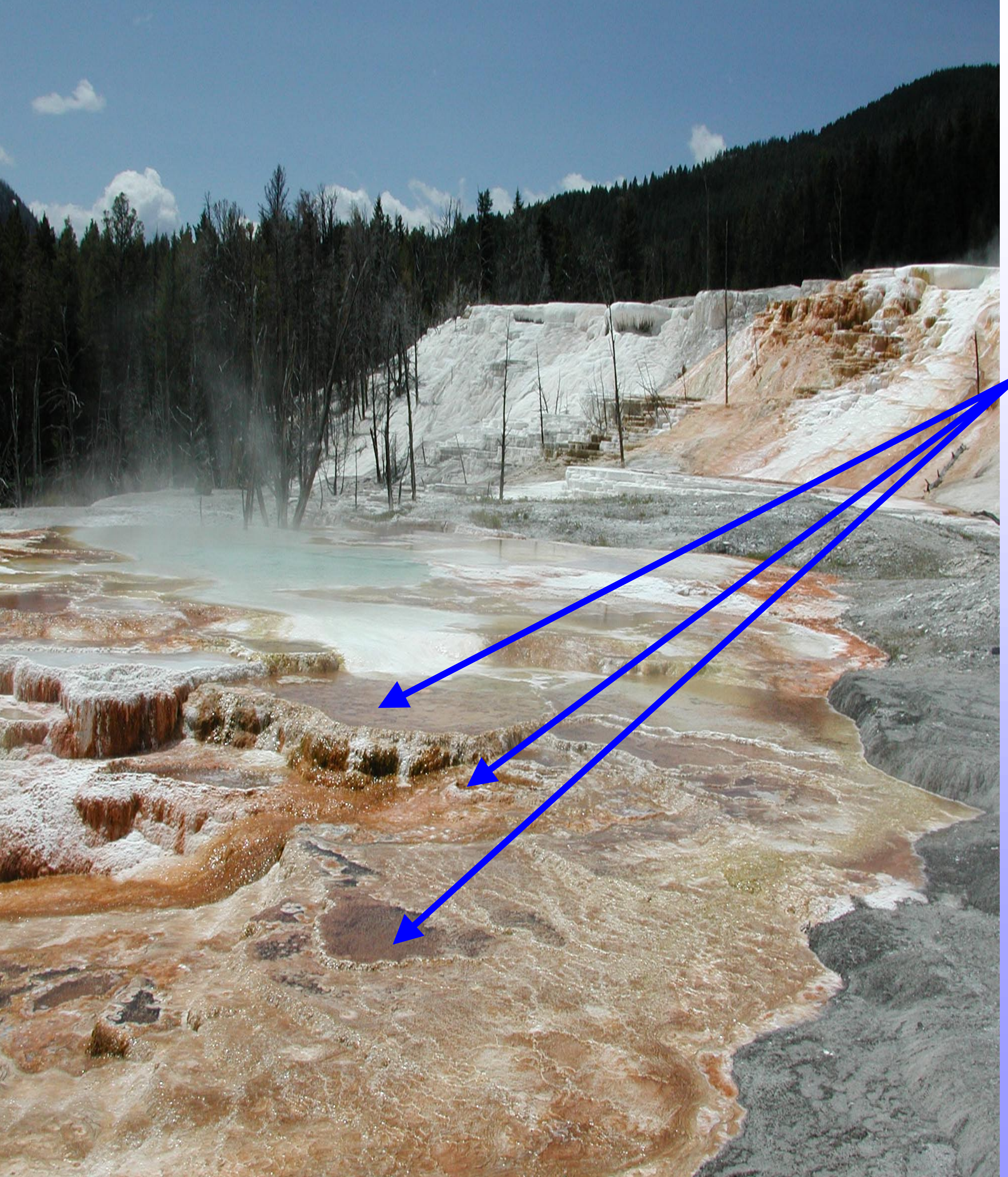


Travertine terraces at hot springs



Study Area
Montana
Yellowstone
National
Park
Idaho
Yellowstone Lake
Wyoming
= travertine deposits
Yellowstone River
Northern Park
Boundary
Gardiner
Montana
Mammoth
Hot Springs
Wy
N
Gallatins
Gardner River
5 km

Angel Terrace (Nov 2002)



Pond Features

Variety of temperatures (30°-62°C)

Occur on many scales

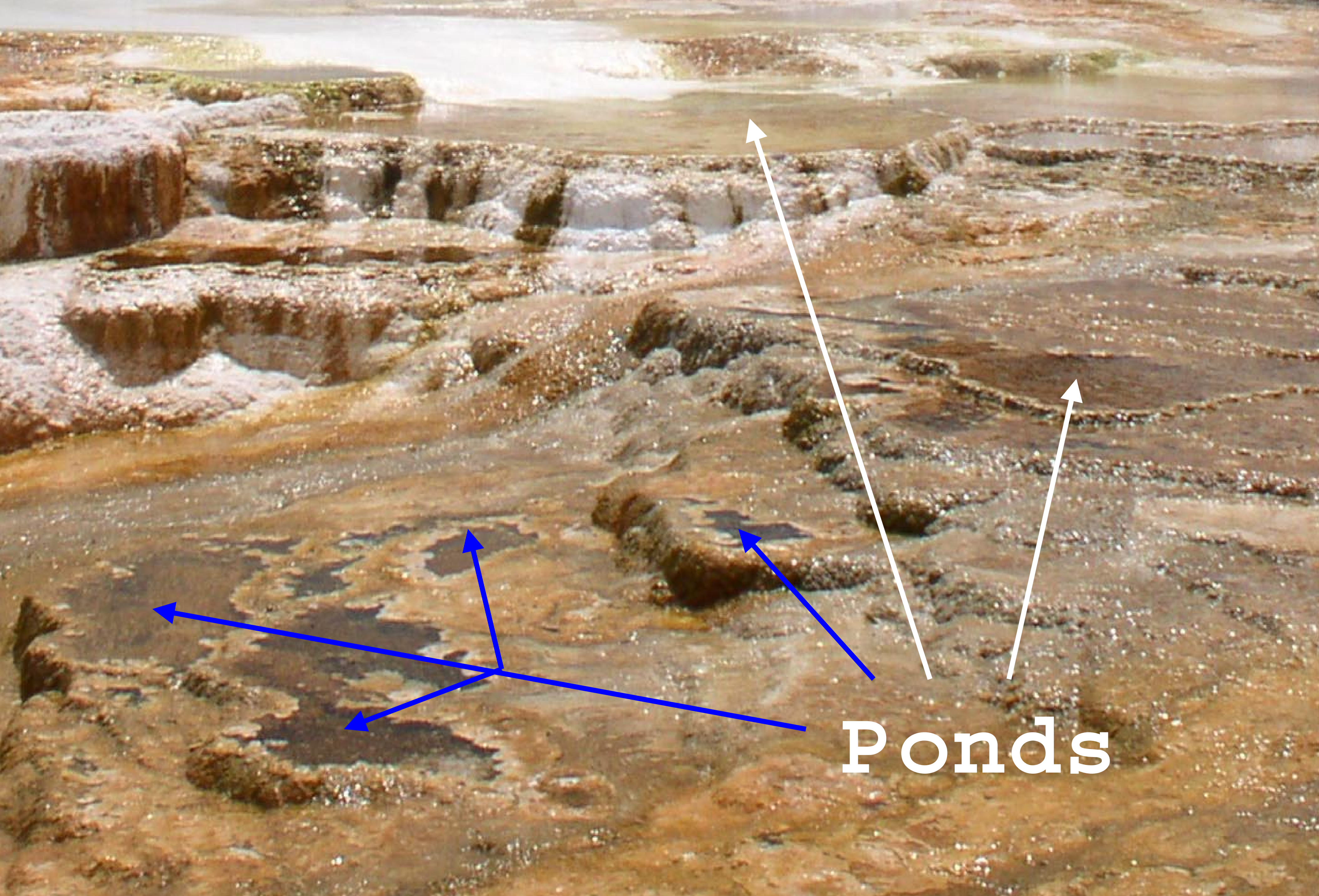
High deposition rates, up to millimeters/day

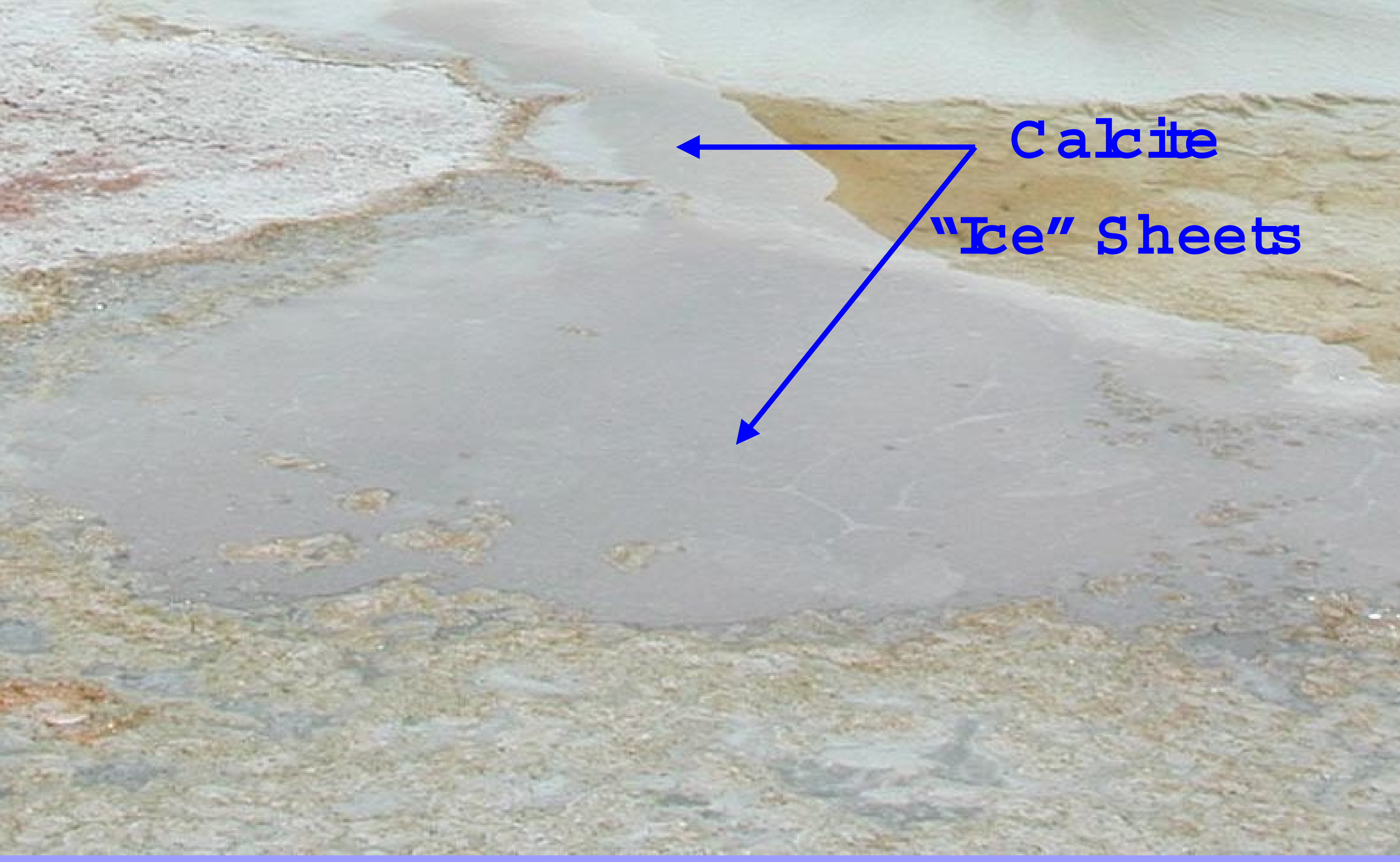
Aragonite needle shrubs form at higher temps

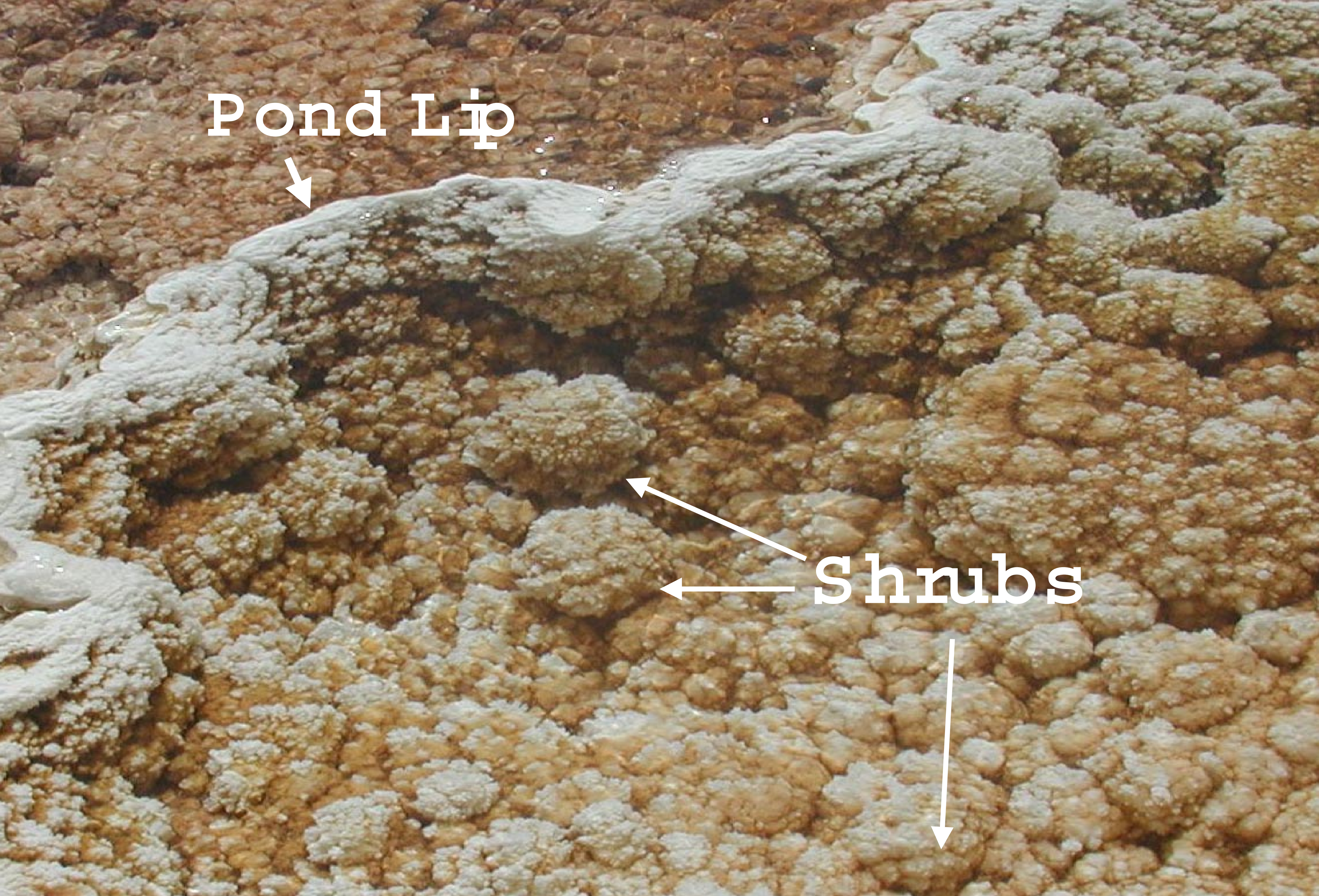
Calcite Ice sheets often collapse and settle to bottom

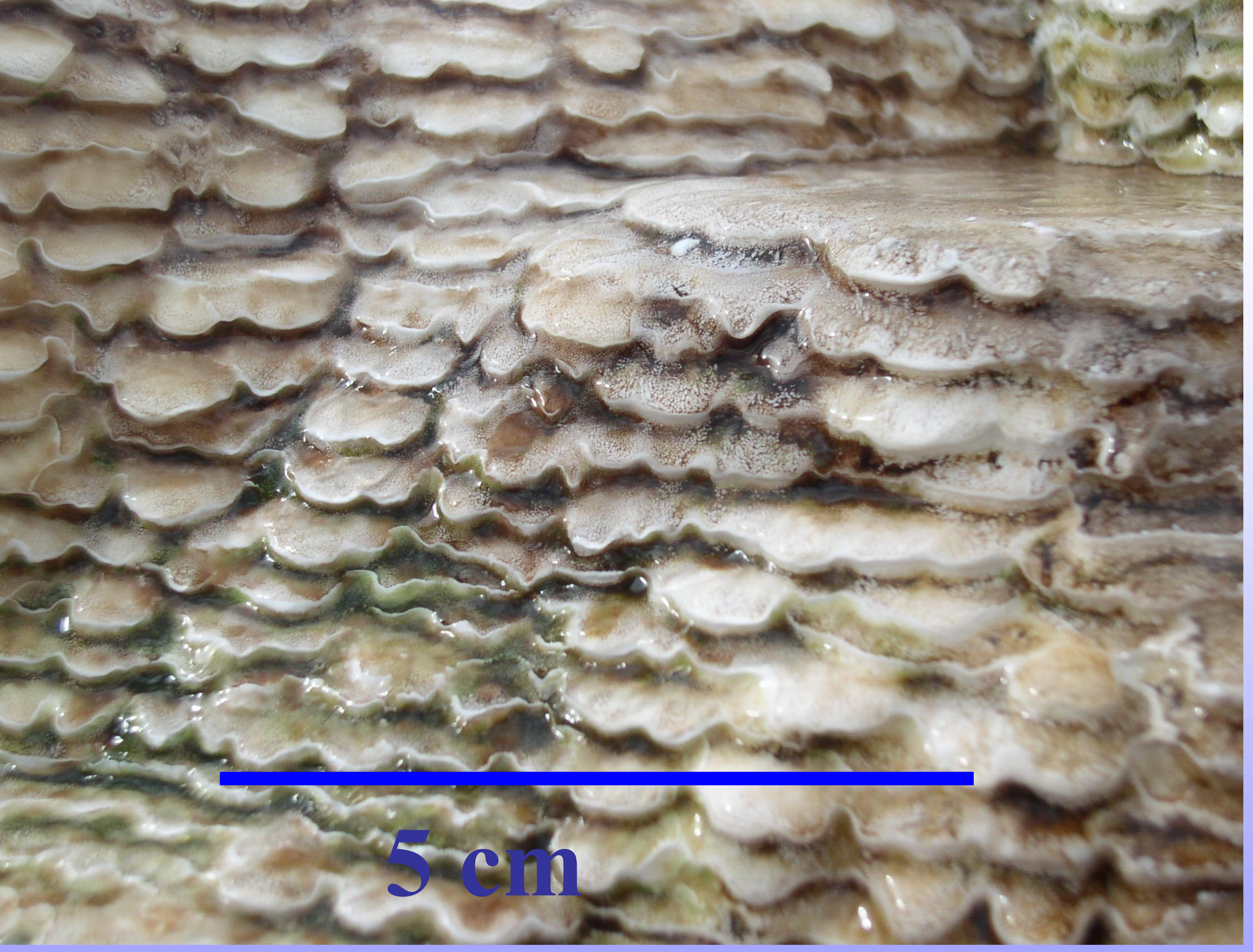
Calcified air bubbles

Ridged networks of calcite/aragonite at lower temps

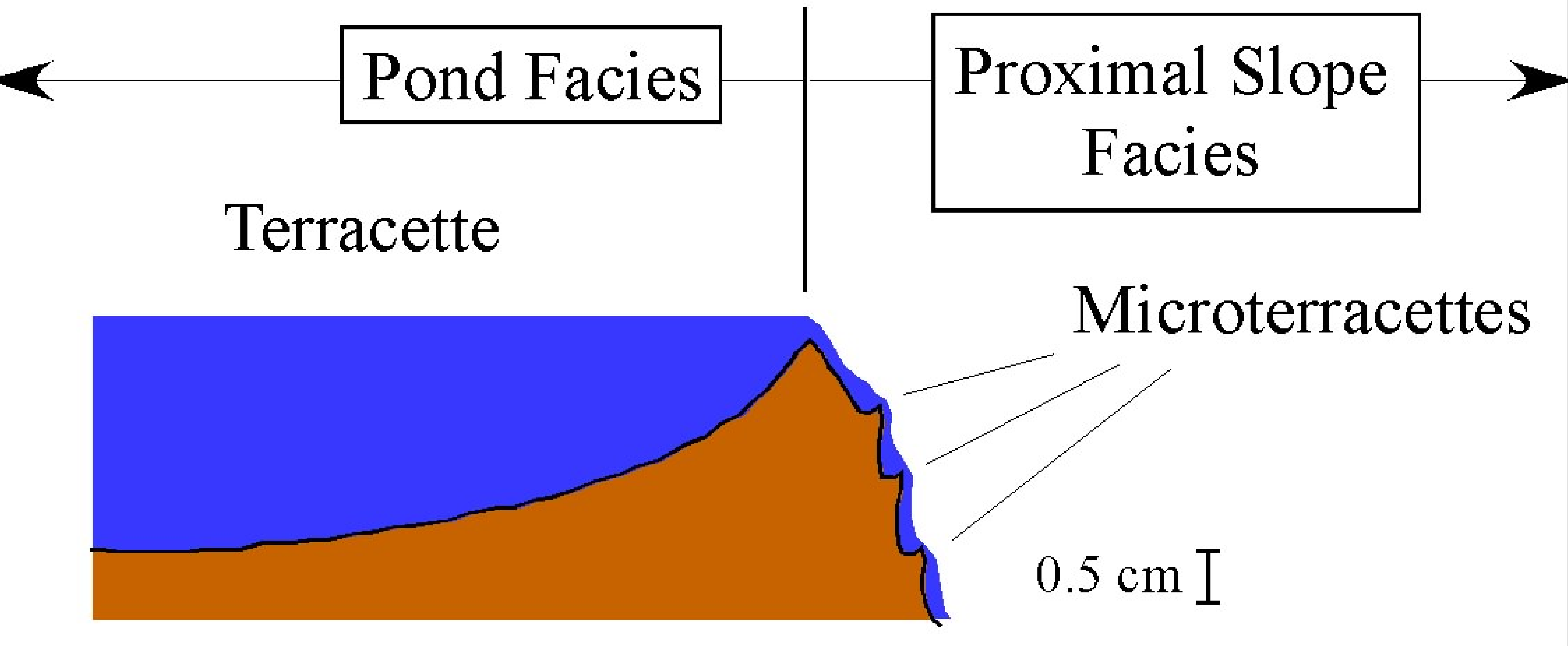

Ponds

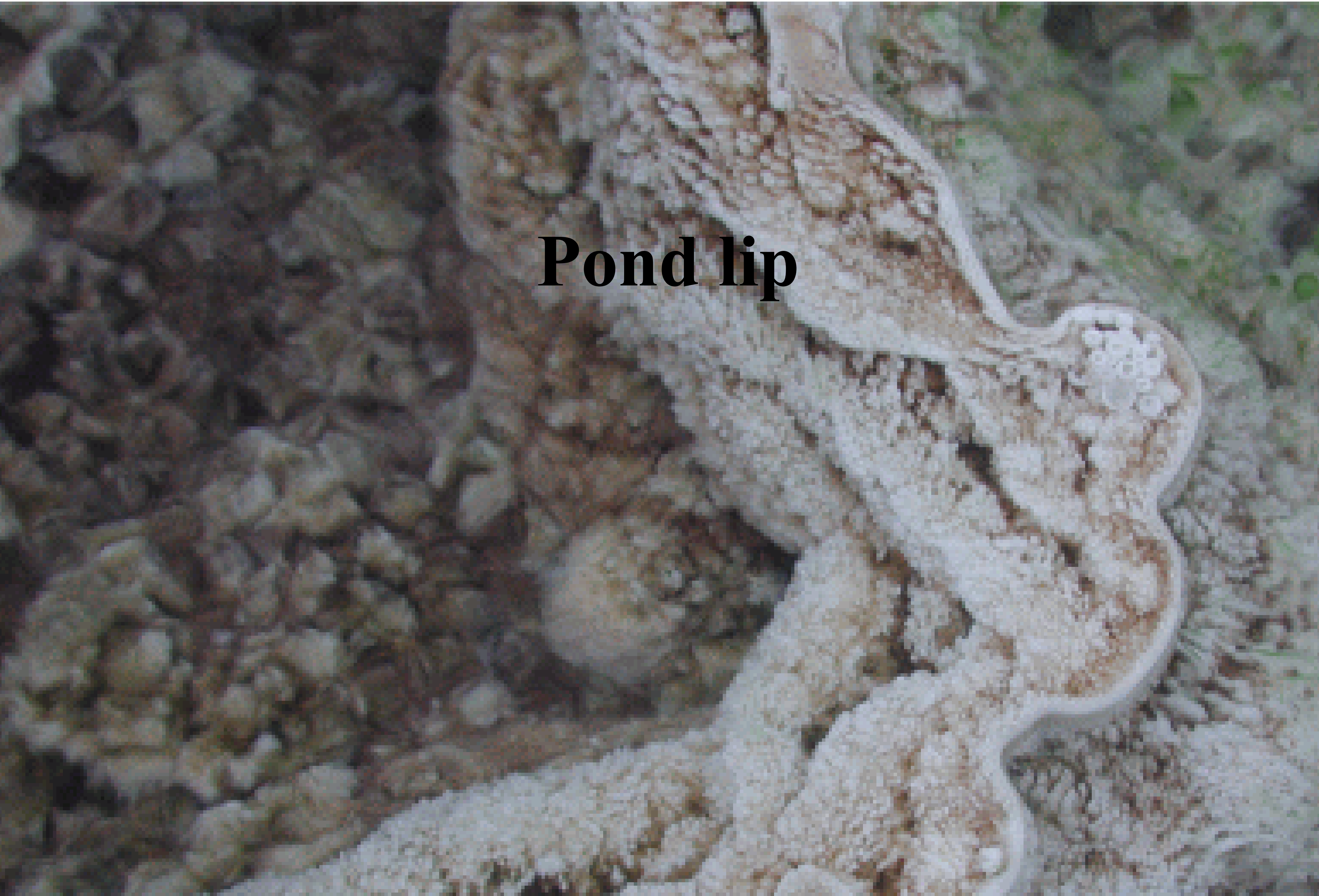

Calcite
"Ice" Sheets


Pond Lip
Shrubs



Microterracettes
on edge of ponds.

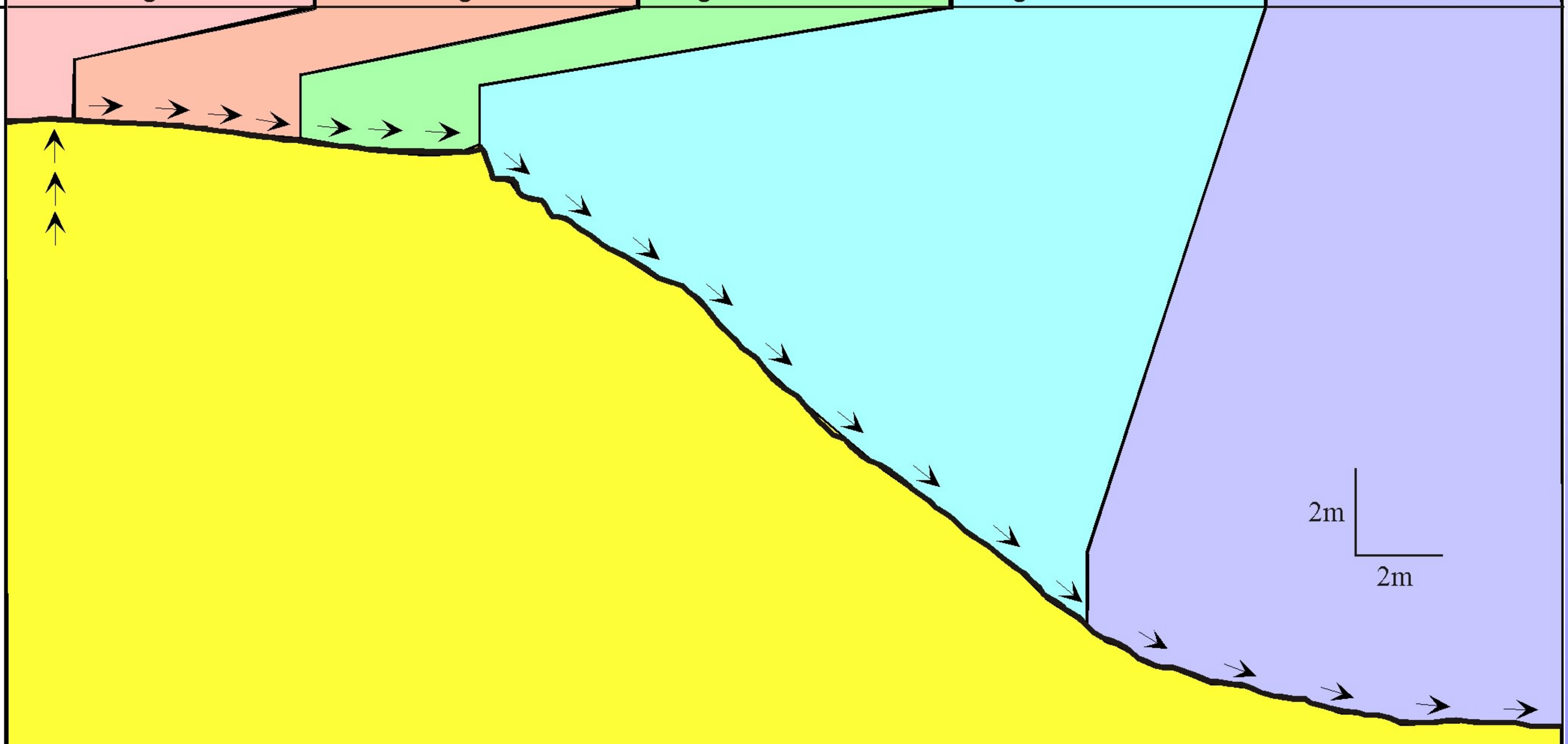

Pond Facies
Proximal Slope Facies
Terracette
Microterracettes
0.5 cm


Pond lip


Apron channel - fingers of microbes, encrusted with aragonite

Travertine Facies Model

Facies	Vent	Apron/Channel	Pond	Proximal Slope	Distal Slope
Temp ^{o}C	71 - 73	69 - 74	30 - 71	28 - 54	28 - 30
pH	7.04 - 7.13	7.45 - 7.21	7.82 - 7.67	7.97 - 8.17	7.90 - 8.34
Alk meg/l	640 - 647	646 - 648	508 - 523	431 - 436	376 - 377
Minerals	aragonite	aragonite	aragonite and calcite	aragonite and calcite	calcite



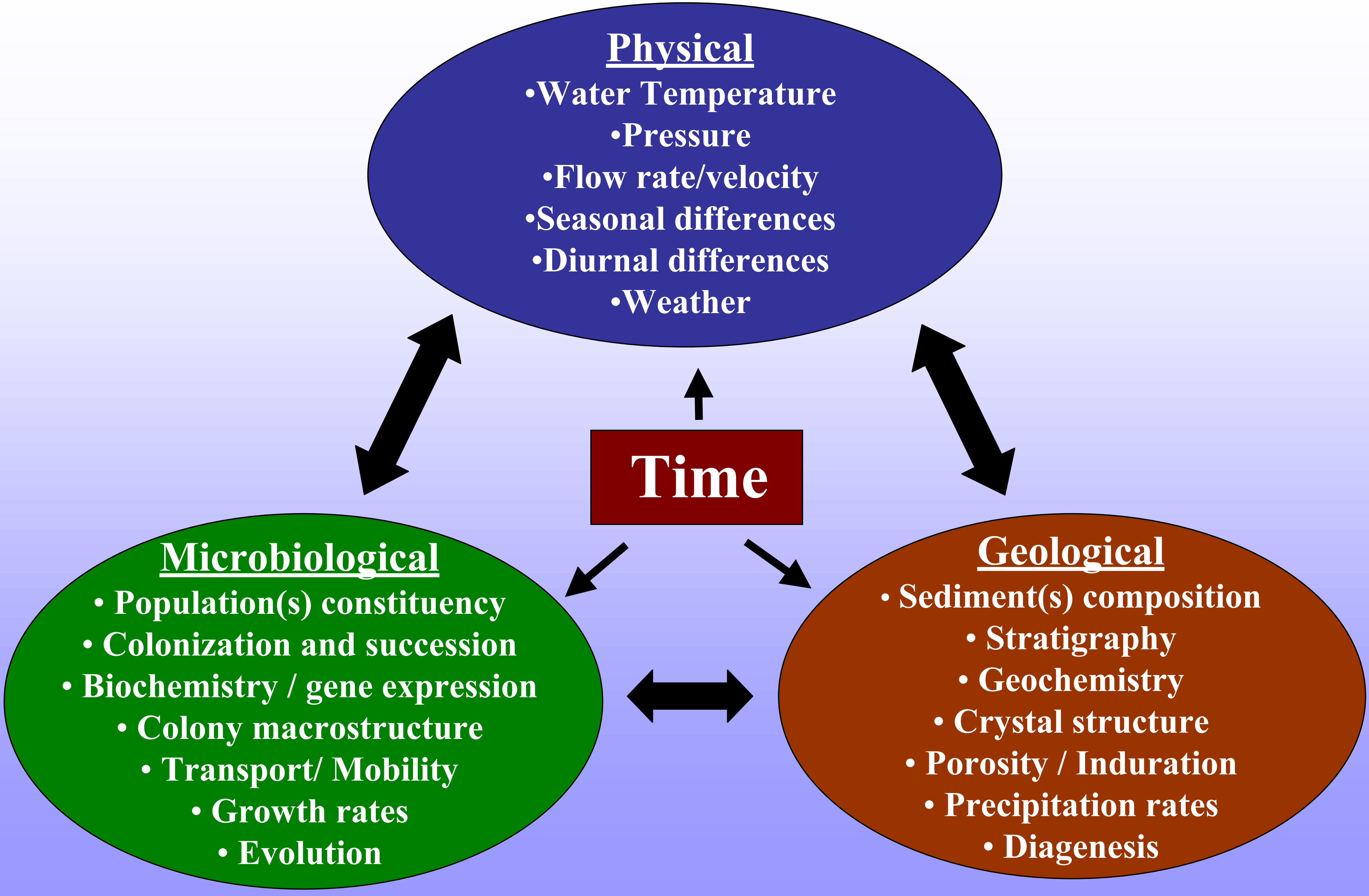
Constructed independent of microbial analyses

Fouke et al. (2000)

Section through shrubs

IOIS
ENTS ONLY!
Micro Order Cen
Lower Level of th ni Union
1401 West Gr
217-244-793
M-F 9:00AM 0PM
SERVICE
Compu
Centra
1609
217-2
M-F 8

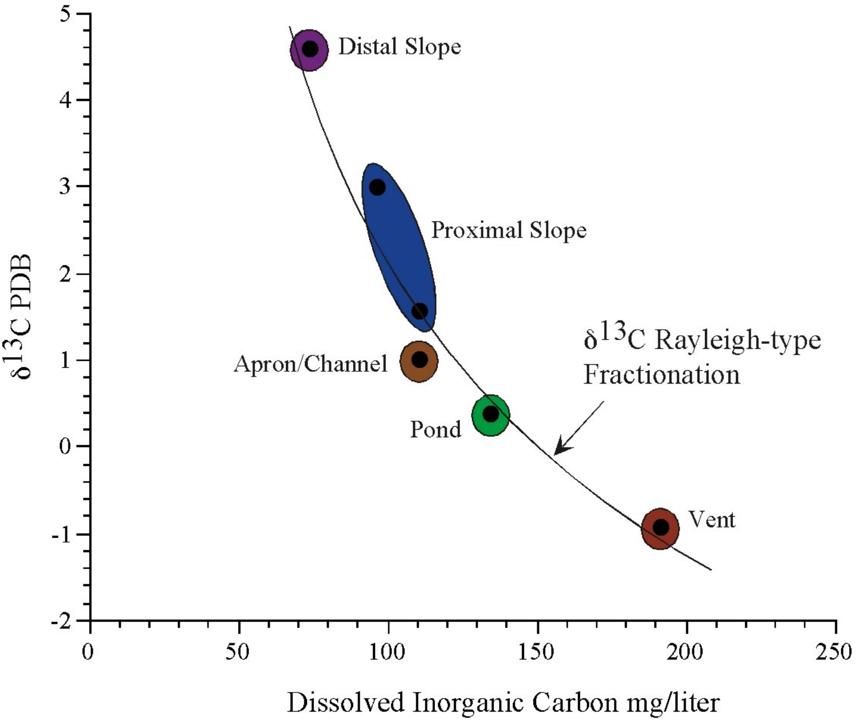

910913.7H1
004589 8.0 kV X1.80K 16.7μm


Physical
•Water Temperature
•Pressure
•Flow rate/velocity
•Seasonal differences
•Diurnal differences
•Weather
Time
Microbiological
• Population(s) constituency
• Colonization and succession
• Biochemistry / gene expression
• Colony macrostructure
• Transport/ Mobility
• Growth rates
• Evolution
Geological
• Sediment(s) composition
• Stratigraphy
• Geochemistry
• Crystal structure
• Porosity / Induration
• Precipitation rates
• Diagenesis

Key Scientific Questions

- Role of microbes versus the environment?
  - Can microbes locally alter CO_2 concentration, driving the large-scale crystallization and geomorphology?
  - Microbial cells act as passive or active nucleation sites?
- Dynamics of landscape evolution?
  - Fluid flow + crystallization (universal stochastic dynamics?)
  - Statistical characterization of geomorphology
  - Biological terra-forming (globally important deposits)
- Identification of ancient microfossils?
  - Bacteria as sensitive indicators of paleoenvironments?

Water chemistry



$$\ln \frac{C_t}{C_{t0}} = \left(0.5\left(\frac{1}{\alpha T} + \frac{1}{\alpha T \times \alpha S}\right) - 1\right) \ln \frac{M_t}{M_{t0}}$$

equation from Michaelis et al. (1985)

C = $\delta^{13}C$ ratio

T = total isotopic fractionation factor
(cumulative mole fraction for all carbonate species)

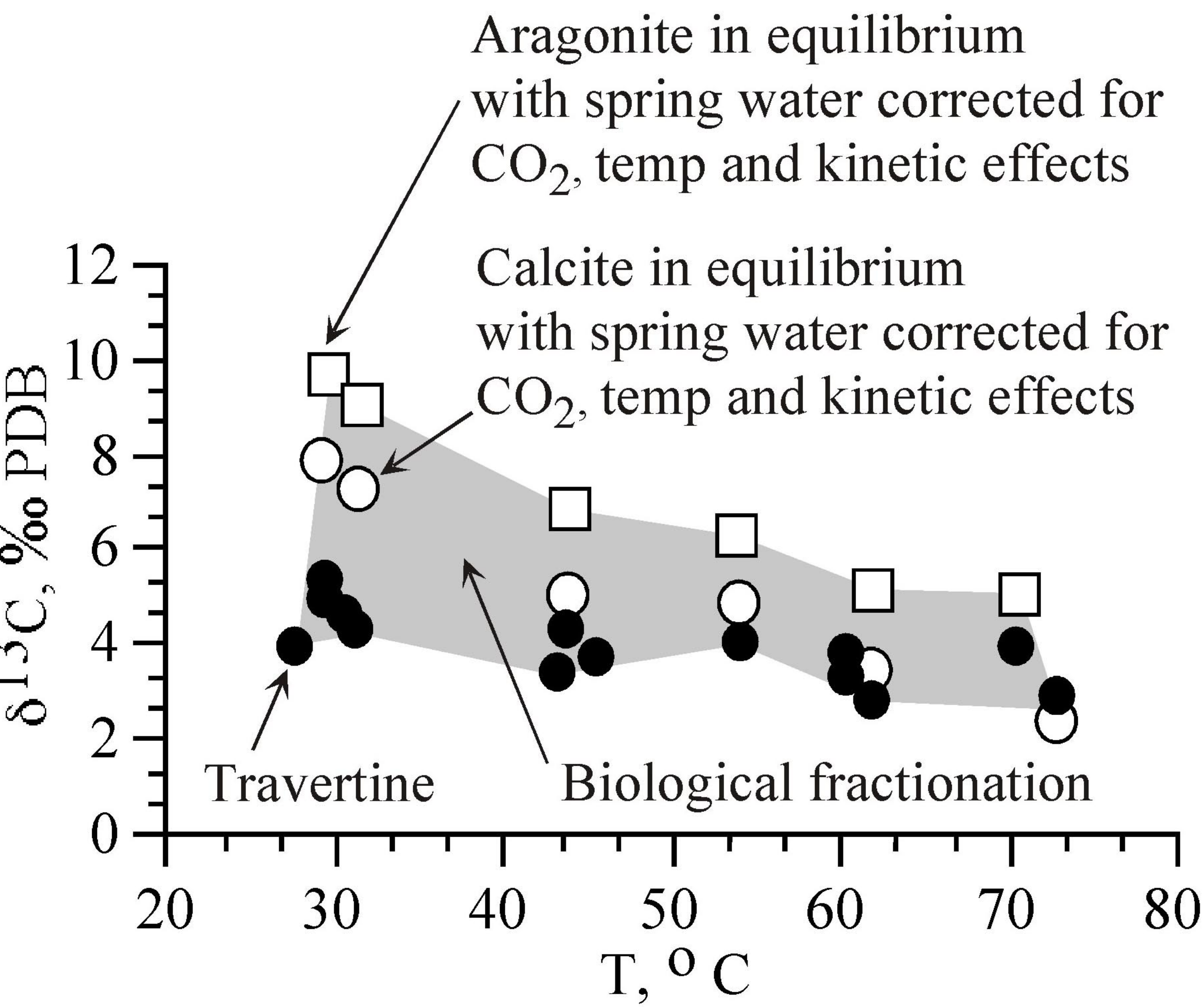
S = ratio of inorganic carbon concentration in gas versus solid

M = total dissolved inorganic carbon concentrations

Water chemistry primarily determined by CO_2 degassing.

C^{13} content follows theoretical predictions for the different facies

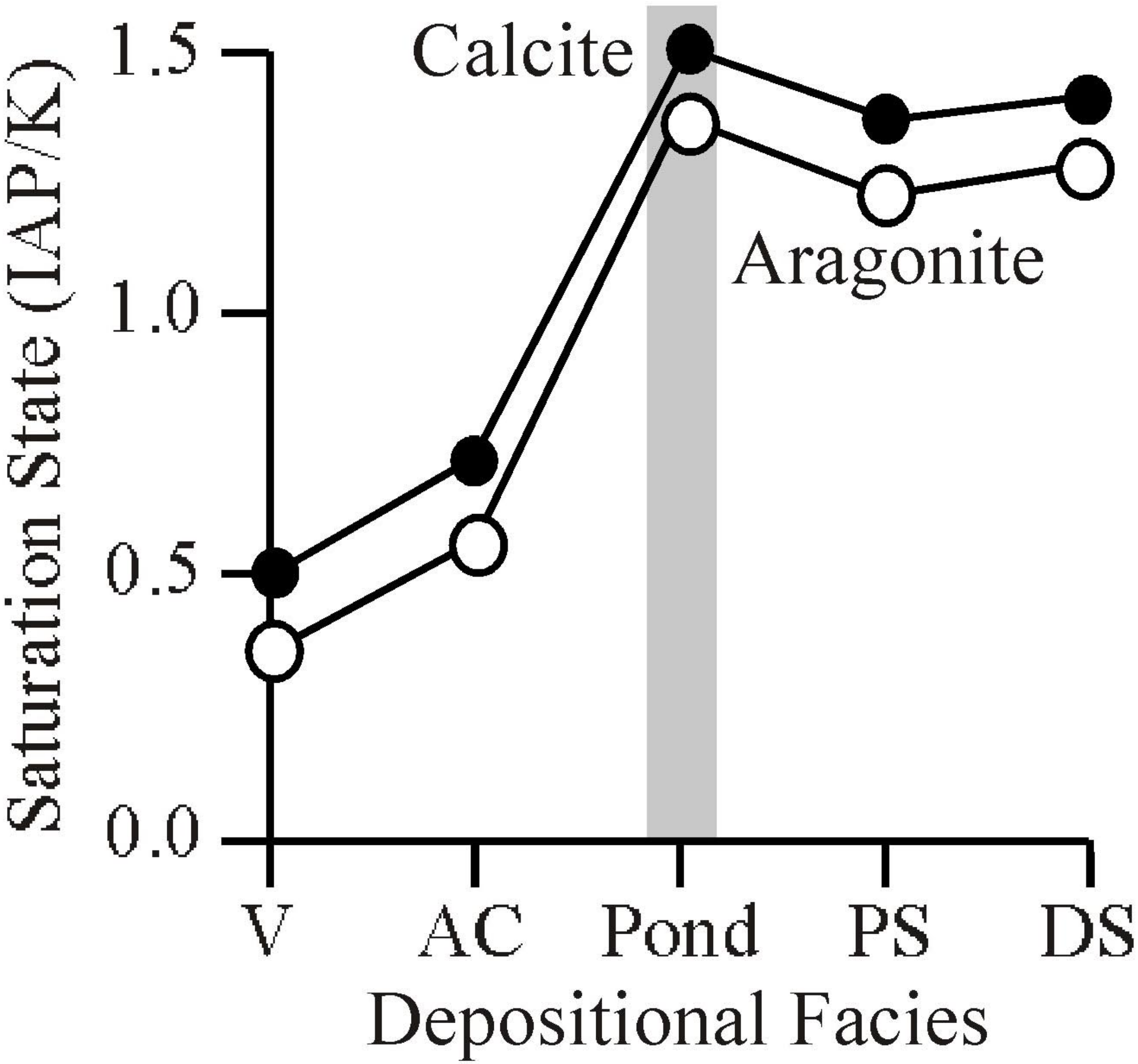
Disequilibrium in isotopic fractionation



C^{13} concentration as a function of temperature indicates anomalously low level.

Biologically driven disequilibrium?

Saturation state at each facies

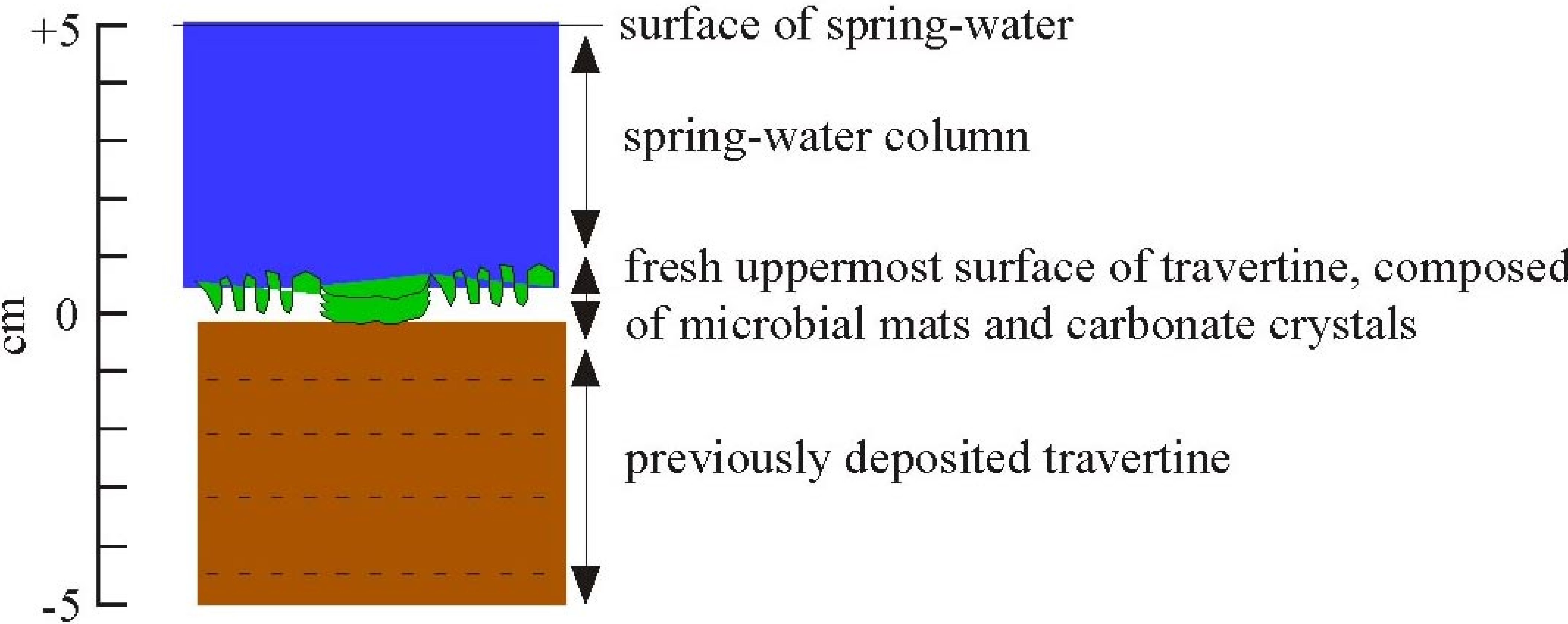


Normalised ion activity product shows degree of saturation at different facies.

Undersaturation above pond facies correlated with bacteria changing from autotrophic to heterotrophic metabolism?

Analysis of microbial biodiversity

Goal: spatial arrangement of microbial species?



“Species” or OTU Definition

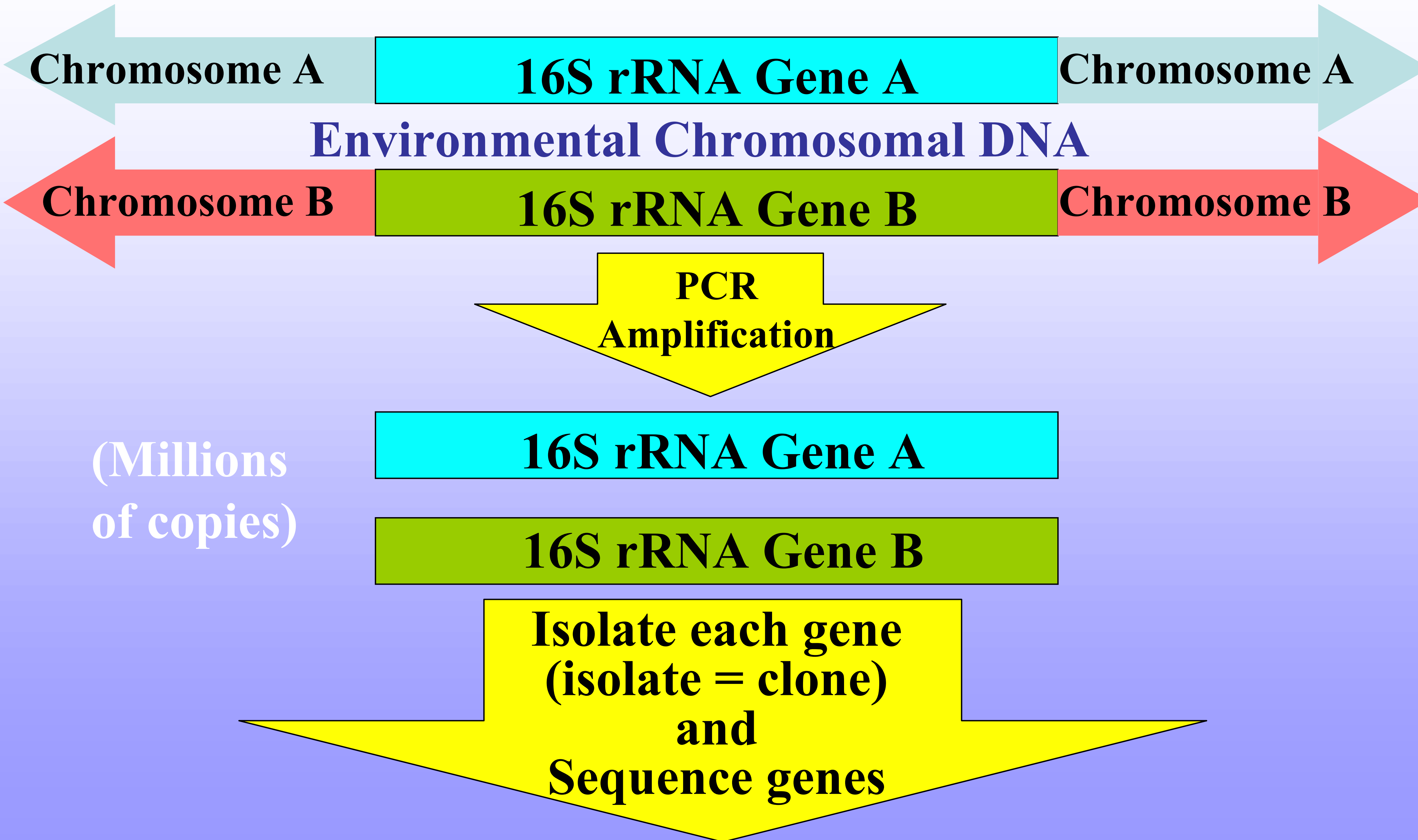
Problem: “Species” based solely on gene sequences is controversial and inconsistent

Problem: ~ 98+% of the microbes at Mammoth Hot Springs have not been (can not be?) cultured

Solution:

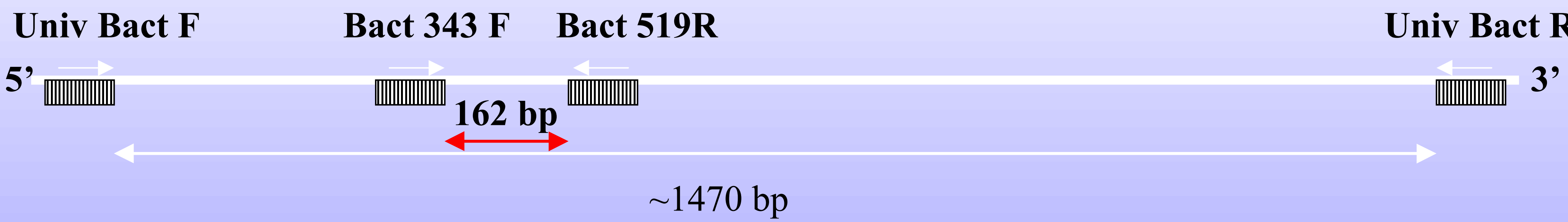
- define an <u>Operational Taxonomic Unit</u> (OTU)
- based on % similarity of 16S rRNA gene sequences
- OTU analyses at 3%, 1%, and 0.5% differences

Simplified Molecular Biological Analysis



16S rRNA Gene Sequence Primers

Primer:	Primer Sequence:	Primer Length	*E. coli* Position
Bact 343 F	5’ TAC GGR AGG CAG CAG	15-mer	343 - 357
Bact519 R	5’ GWA TTA CCG CGG CKG CTG	18-mer	536 - 519

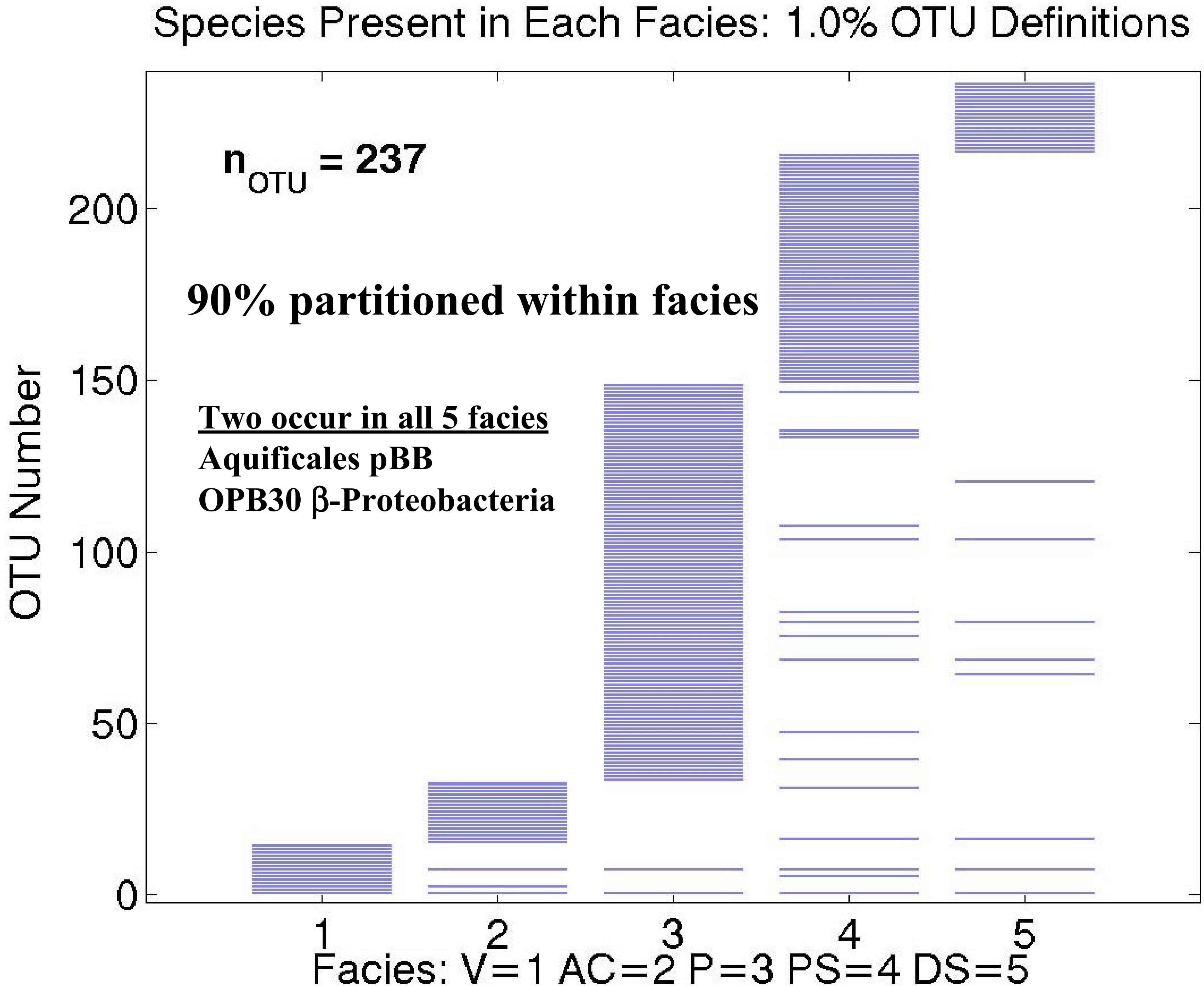


= location of primer sequence and its orientation

= area of broad range sequence conservation (sequence is virtually the same in all bacteria)

= area between primers (not including the primer sequences)

= section of the 16S rRNA sequence that is highly variable between different bacterial divisions, conservation exists only between closely related species



Species Present in Each Facies: 1.0% OTU Definitions
n_{OTU} = 237
90% partitioned within facies
Two occur in all 5 facies
Aquificales pBB
OPB30 β-Proteobacteria
OTU Number
0
50
100
150
200
1
2
3
4
5
Facies: V=1 AC=2 P=3 PS=4 DS=5

Overlap between facies

		0.5%	O.T.U.		
	V	AC	P	PS	DS
V	23	2	3	5	2
AC		24	2	3	2
P			167	17	10
PS				114	8
DS					40

		1.0%	O.T.U.		
	V	AC	P	PS	DS
V	15	3	2	3	2
AC		21	2	4	3
P			118	14	7
PS				84	6
DS					29

		3.0%	O.T.U.		
	V	AC	P	PS	DS
V	6	3	2	2	2
AC		20	5	6	4
P			99	14	8
PS				71	6
DS					28

Decrease in OTU % definition

- increases # OTUs
- overlap unchanged

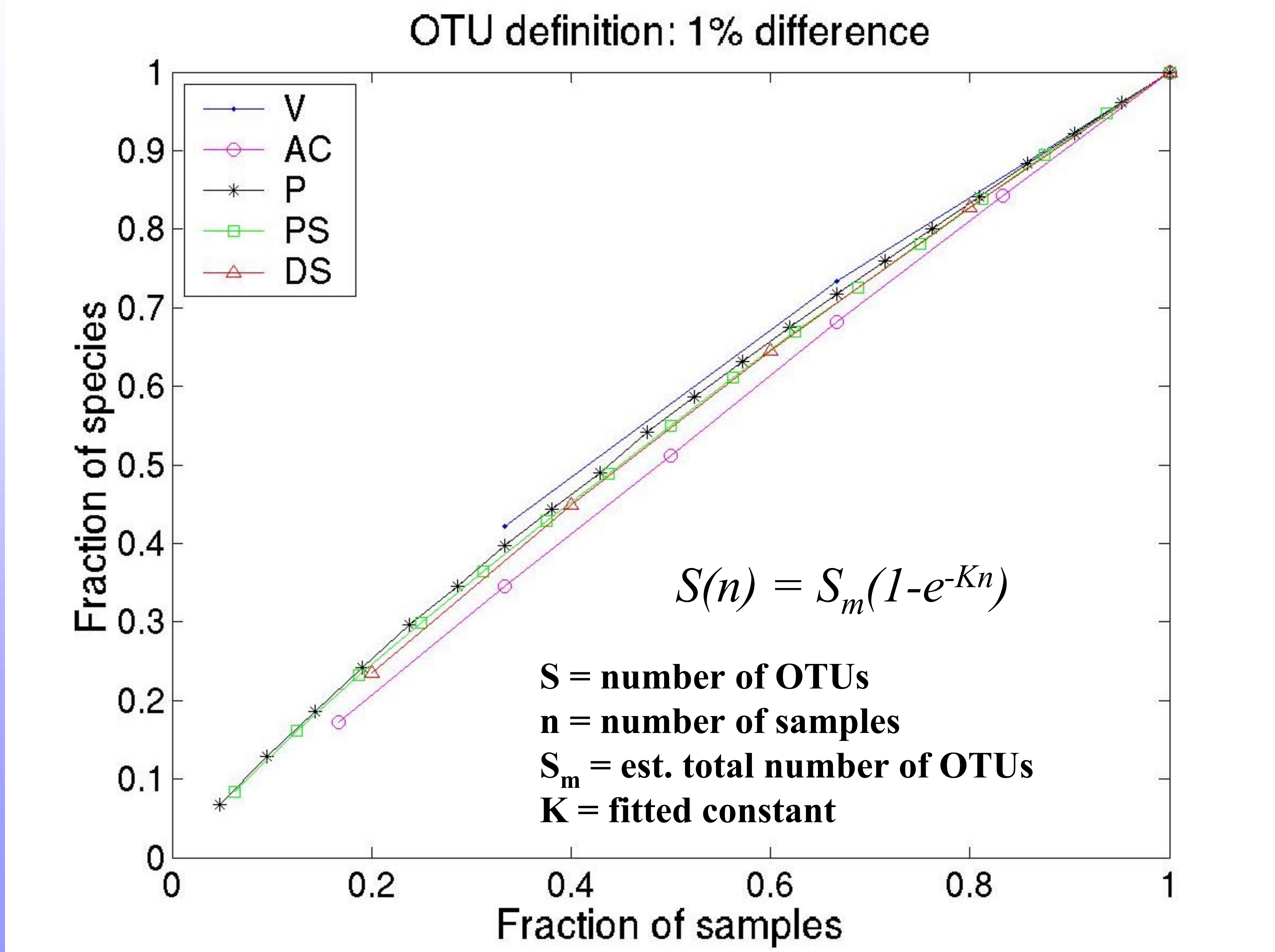
- **Conclusion: extreme partitioning of microbial species between facies**

Estimation of abundance

- **How do we know that we have sampled all the microbes present in a given facies?**
  – Incomplete sampling may cause us to conclude that species are partitioned when in fact they are actually present in more than one facies.

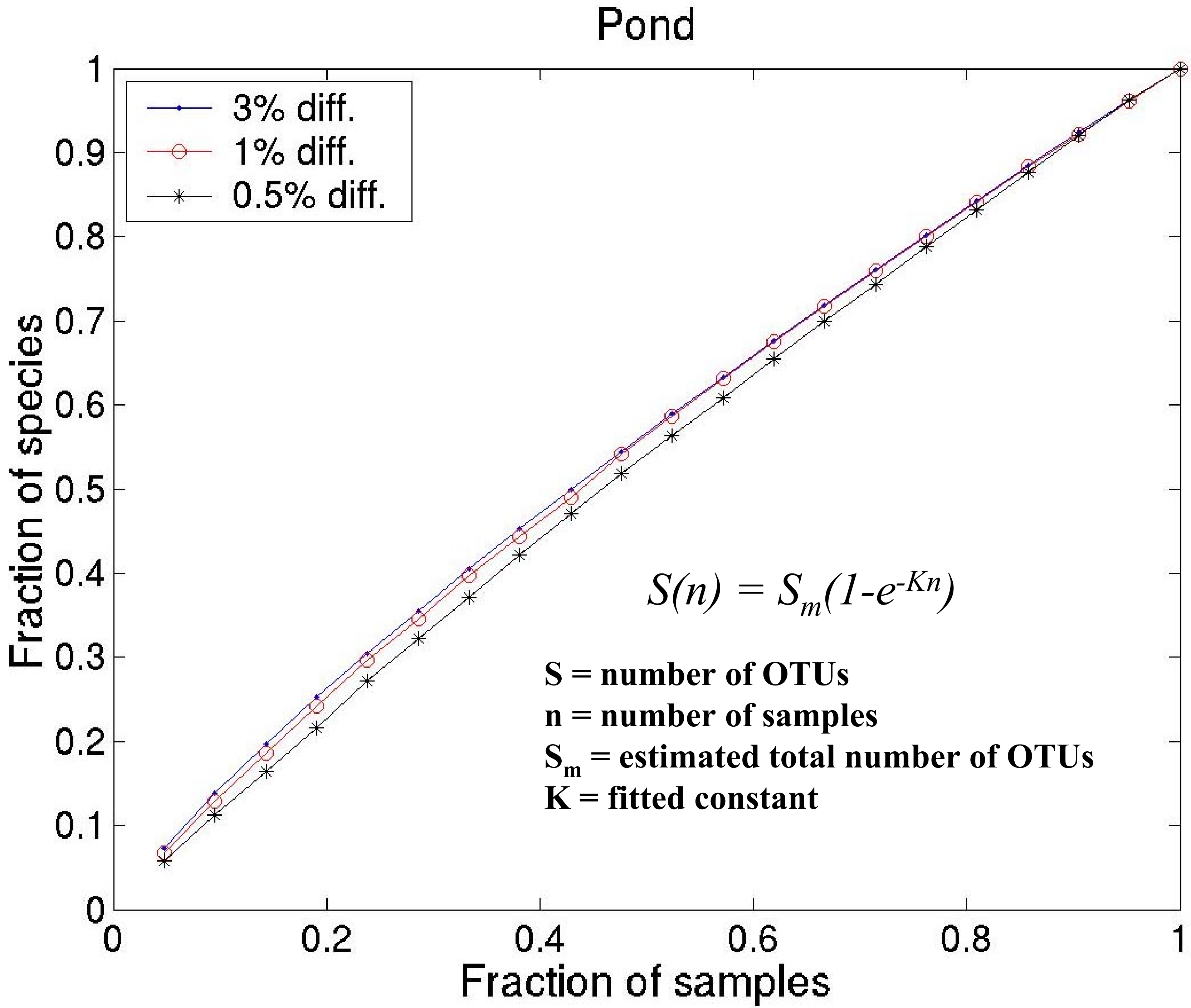
- **Test convergence of sampling**
  – How does the number of OTUs scale with number of samples of microbes? Do we observe saturation indicating convergence?

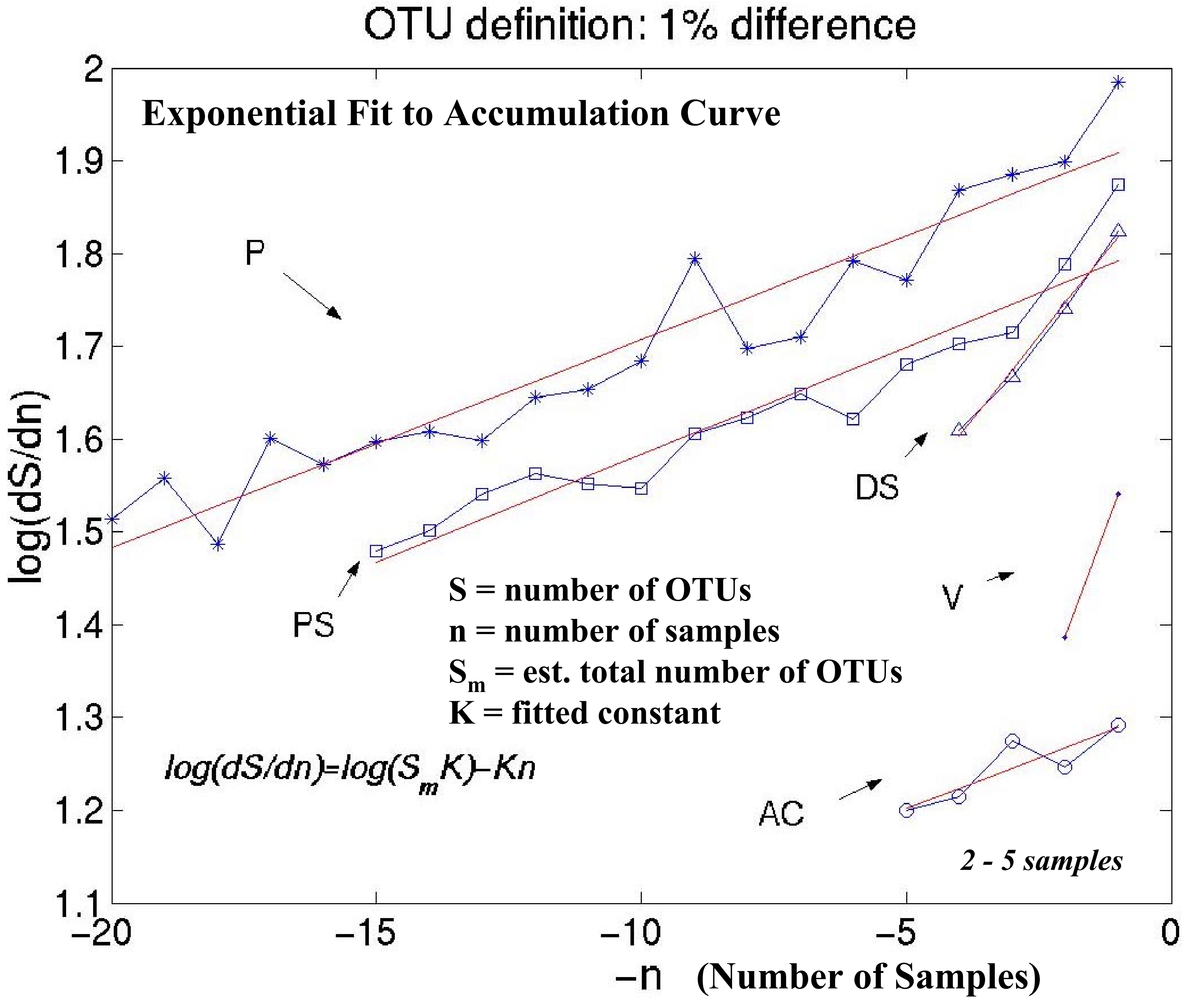
Accumulation Curves

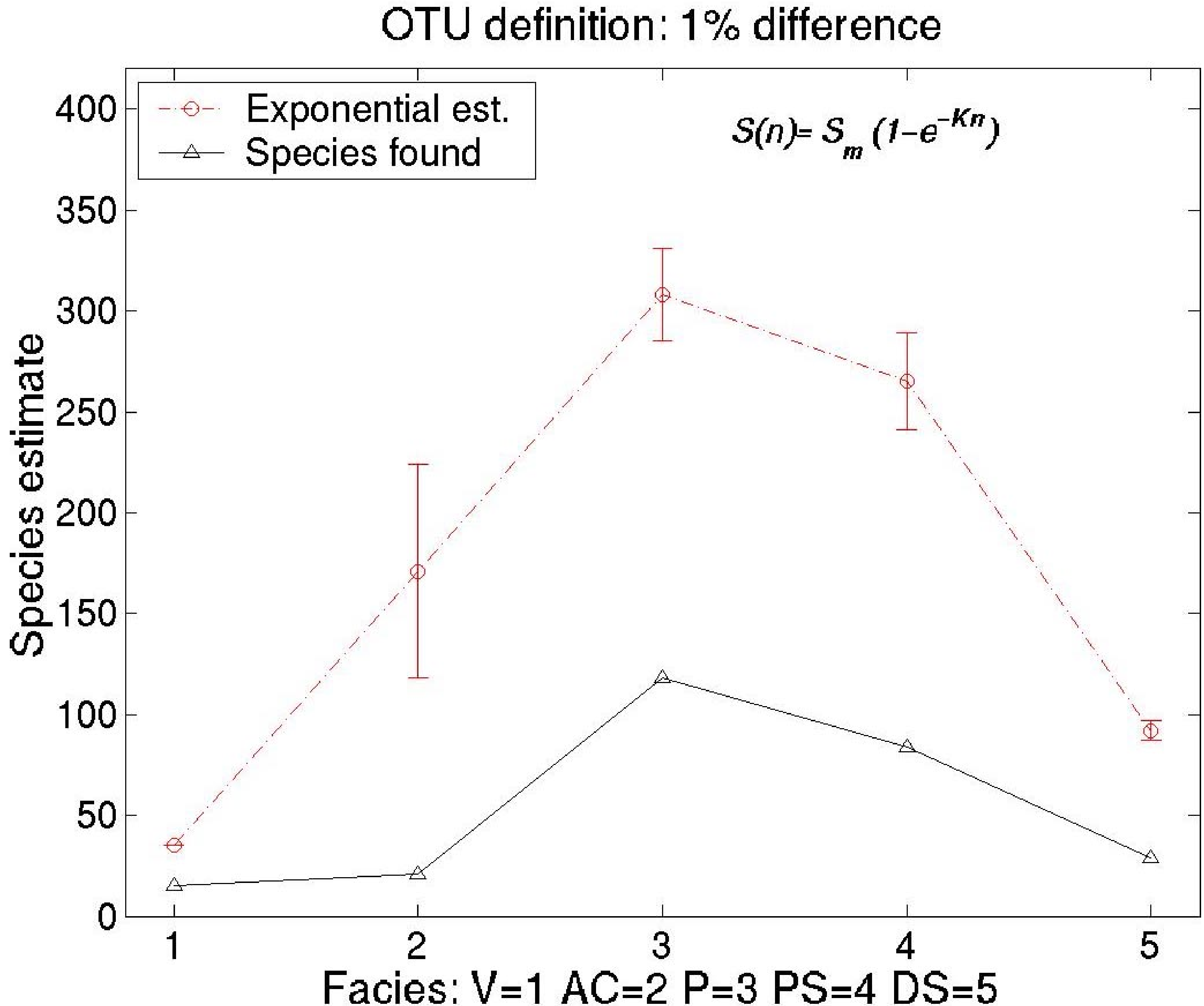


$$S(n) = S_m(1-e^{-Kn})$$

S = number of OTUs
n = number of samples
S_m = est. total number of OTUs
K = fitted constant


Pond
3% diff.
1% diff.
0.5% diff.
S(n) = S_m(1-e^{-Kn})
S = number of OTUs
n = number of samples
S_m = estimated total number of OTUs
K = fitted constant
Fraction of species
Fraction of samples
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0
0.2
0.4
0.6
0.8
1


OTU definition: 1% difference
Exponential Fit to Accumulation Curve
P
PS
DS
V
AC
S = number of OTUs
n = number of samples
S_m = est. total number of OTUs
K = fitted constant
$log(dS/dn)=log(S_m K)-Kn$
2 - 5 samples
log(dS/dn)
2
1.9
1.8
1.7
1.6
1.5
1.4
1.3
1.2
1.1
−20
−15
−10
−5
0
−n (Number of Samples)


OTU definition: 1% difference
Exponential est.
Species found
$S(n) = S_m (1 - e^{-Kn})$
Species estimate
0
50
100
150
200
250
300
350
400
1
2
3
4
5
Facies: V=1 AC=2 P=3 PS=4 DS=5

Comparison of gene sequences

- **Gene sequence identifies most of the microbes and their metabolic characteristics.**
  - Vent: chemolithotropy
  - Pond: phototrophy
  - Distal slope: heterotrophy
- **Greatest biodiversity in pond facies - the facies with the most fluctuations in pH, temperature, water flow rate**

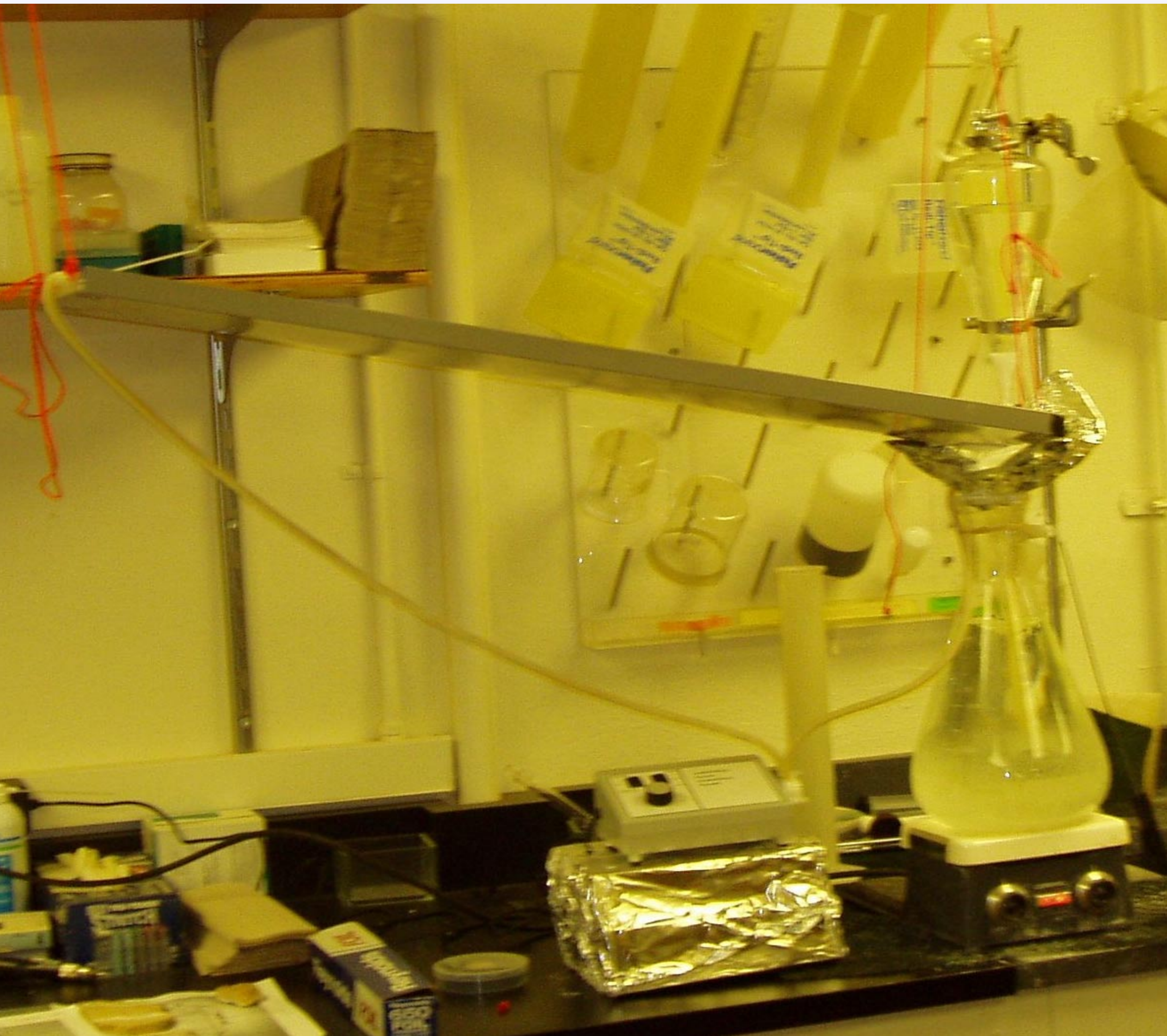
Conclusion of microbe analysis

- **Microbial ecology seems to track the geological facies**
  - this would occur if microbial activity was essential to degassing and carbonate precipitation
  - but may also just indicate microbes are passive markers of water chemistry
- **Next step: measure absolute abundances to determine quantitatively if there are enough microbes to produce precipitation ...**

Laboratory experiments

- **Our goal: create a laboratory analog of pond/terracette system without microbes**
  - Can we reproduce gross geological features such as ponds, terracettes, microterracettes?
    - In a generic flow crystallization setting, with NaCl?
    - In a simulation of YNP water chemistry?

Small Scale Salt Experiment



5° Slope

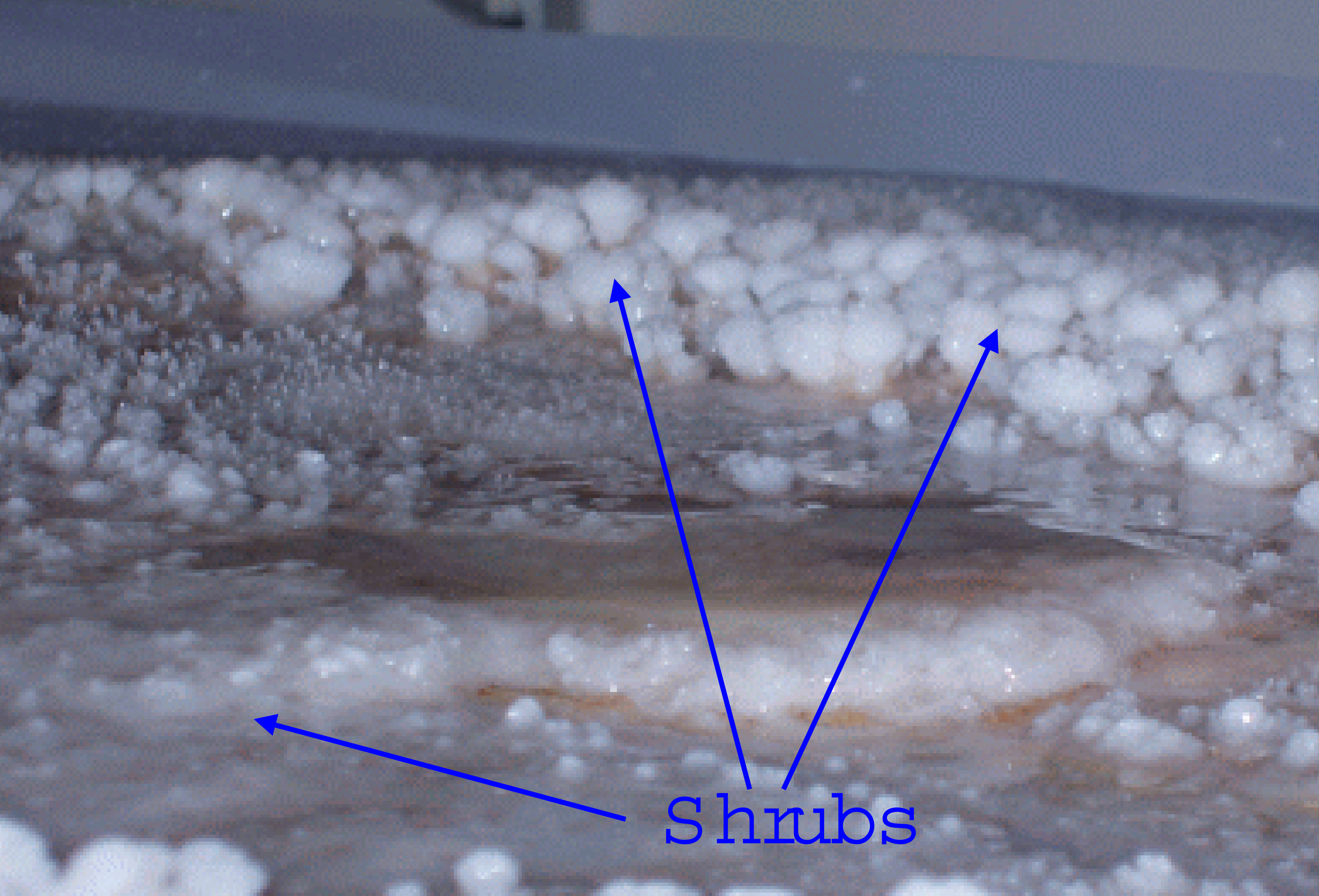
Variable flow rate

H_2O :

-Supersaturated with NaCl

-Heated to approx. 53°

-Recirculated


Shrubs

Large Scale NaCl Experiment

Heated 30 gallon can

- Submerged in 55 gal drum
- Used for mixing salt water

Temperatures

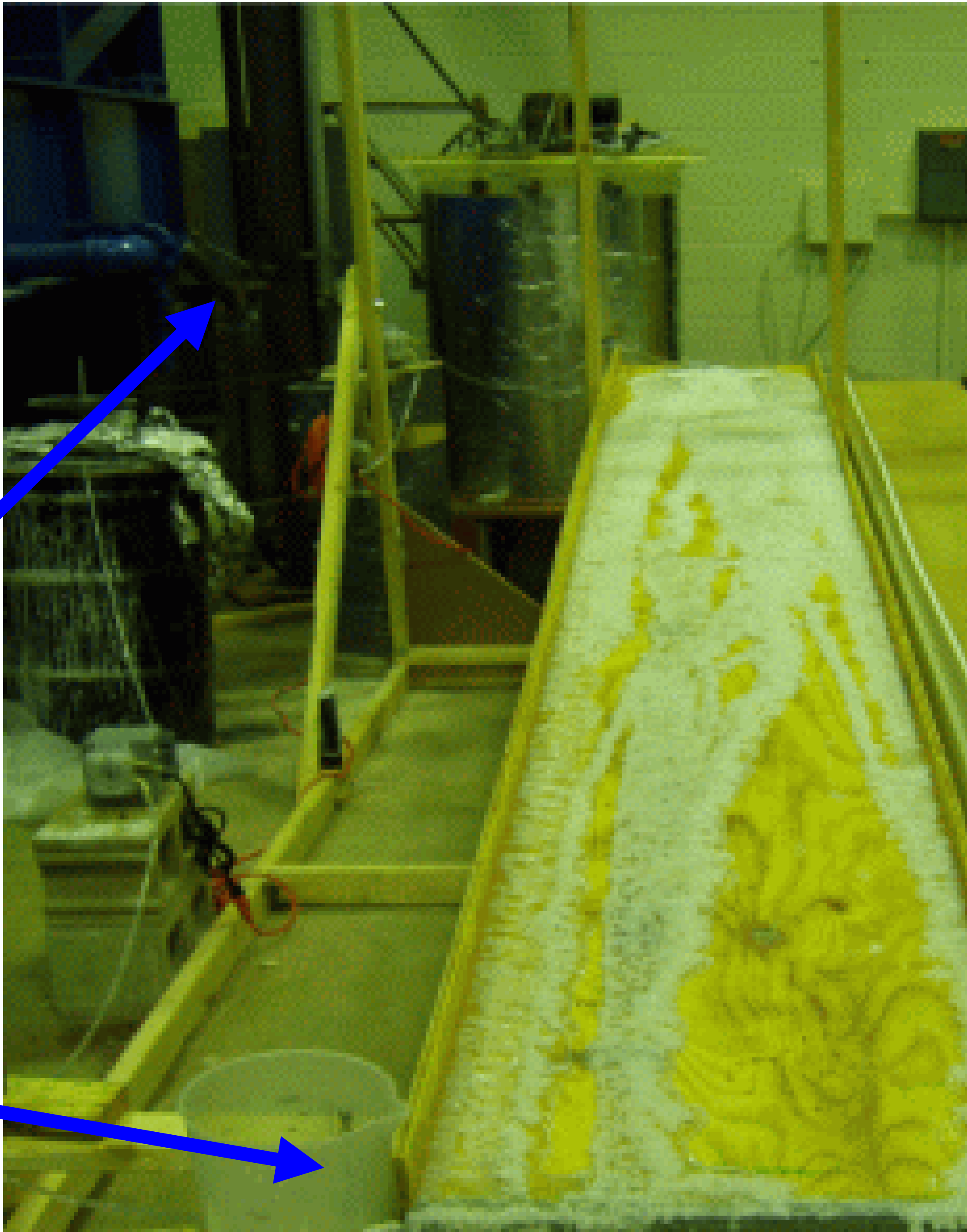
- 60°- 65° at top of ramp
- 40°-45° at bottom

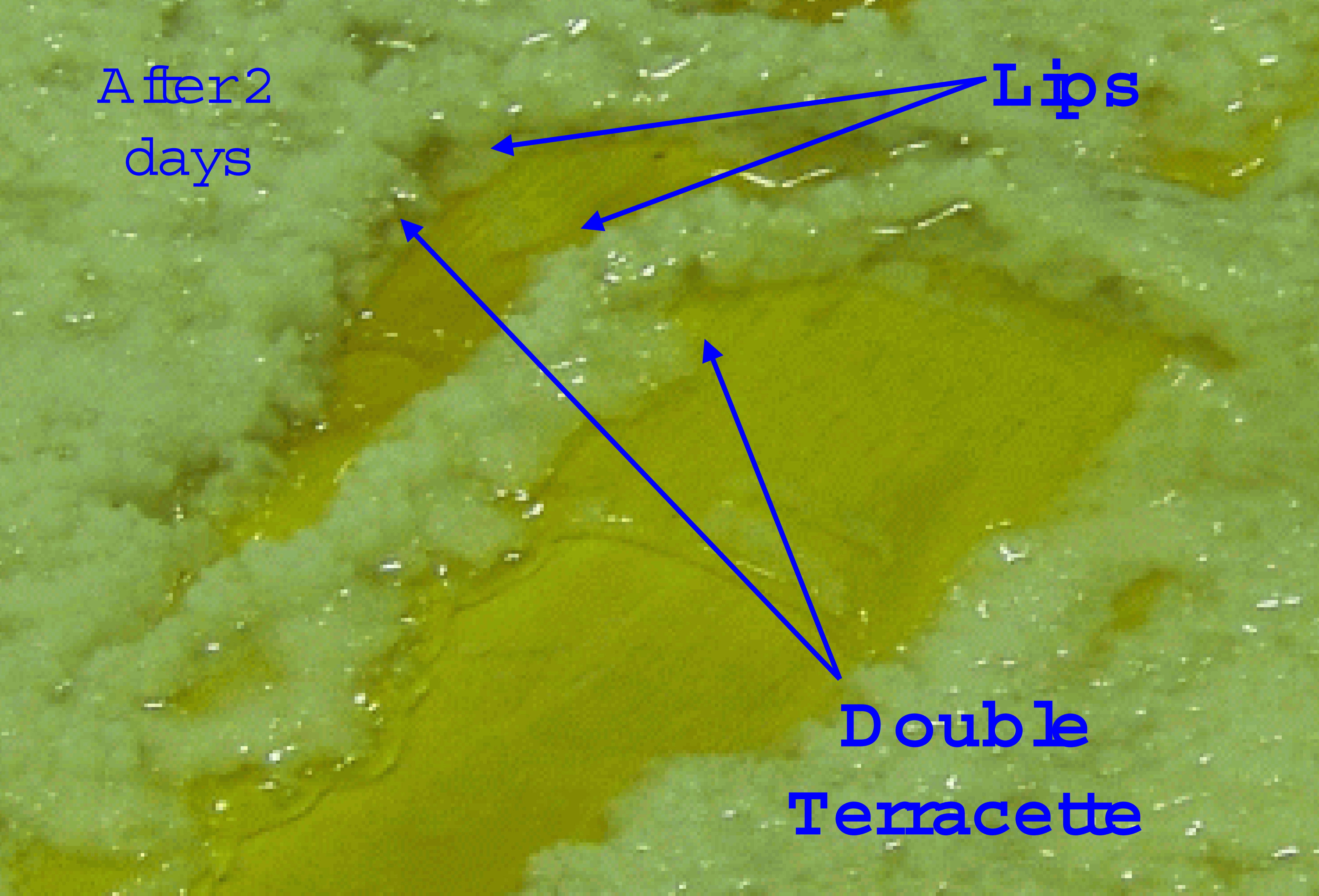
Peristaltic Pumps

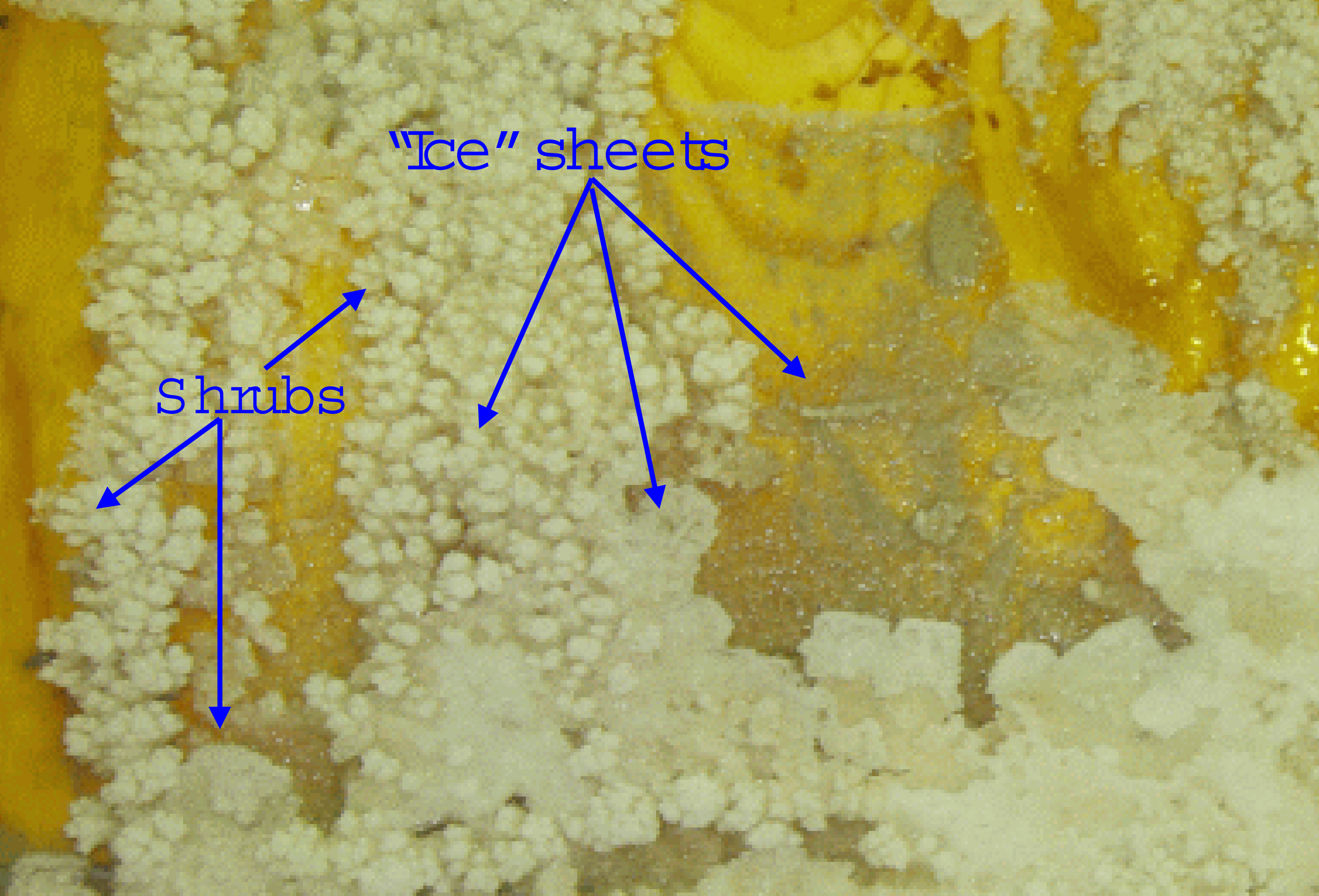
- (flow rate = 0.67 L/min)

Heated collection tub

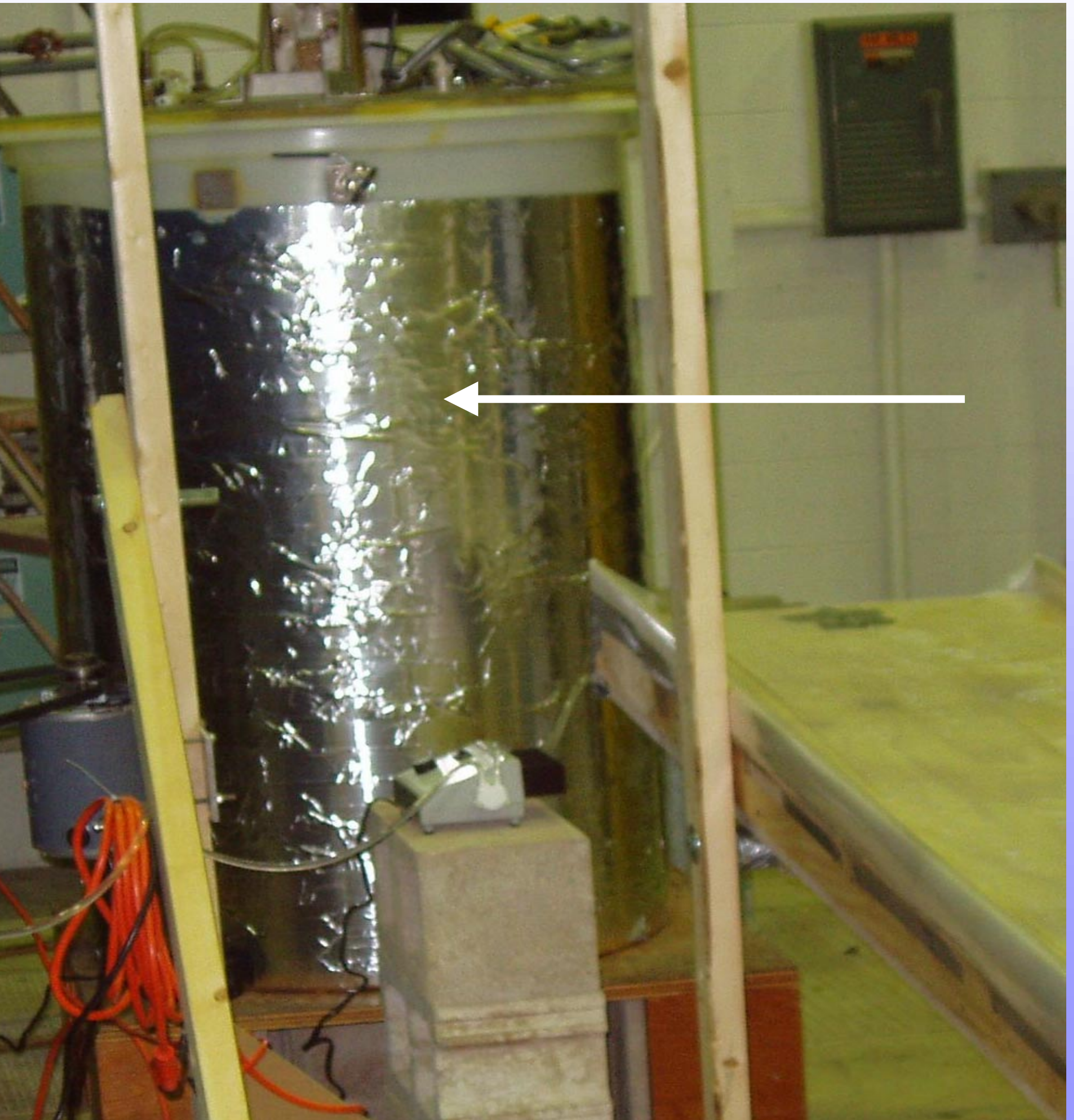
- for recycling water




After 2 days
Lips
Double Terracette


"Ice" sheets
Shrubs

$$CaCO_{3(s)} + H_2O_{(l)} + CO_{2(g)} \rightleftharpoons Ca^{2+}_{(aq)} + CO_3^{2-}{}_{(aq)} + H_2CO_{3(aq)}$$



Large Scale

Calcium Carbonate Experiment

-Initial Pressure 2-3 atm

-Precipitation driven by CO_2 outgassing

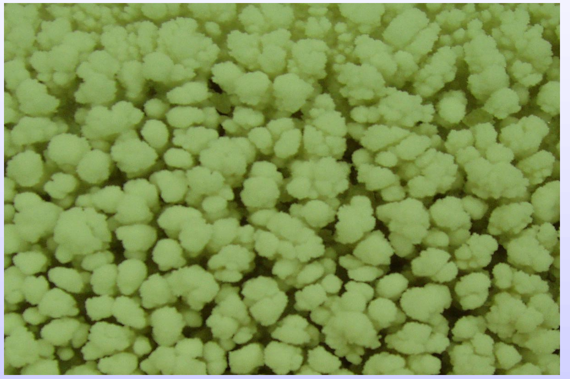
What's Next?

- Re-run Large Scale Salt Experiment
  - Increase slope and flow rate
  - Decrease/eliminate temperature gradient
  - Under supersaturation
  - Color coding with food dye
  - Time-lapse photography
- Large Scale Calcium Carbonate Experiment
  - UV sterilization on one ramp
  - Vary slopes, substrates
  - Color coding and time lapse photography
  - How do patterns formed compare with those at YNP?
- Back to Yellowstone National Park
  - Measure fractal dimensions of ponds, look for power scaling
  - UV sterilization of water channeled from spring
- Examine Shrubs Closer
  - Preserve with epoxy and examine thin sections

Connection between shrubs and Stromatolites?

Stromatolites in Australia
Grotzinger, et al.

Shrubs at Yellowstone National Park



Shrubs from Large Scale NaCl experiment

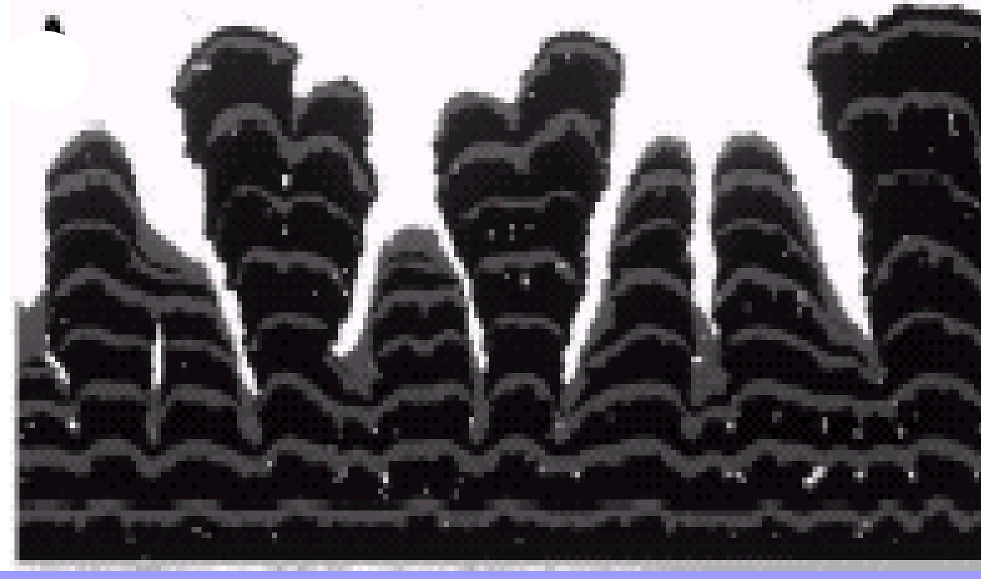
From the fourth edition of the "Glossary of Geology" by Julia A Jackson:

stromatolite: an organosedimentary structure produced by sediment trapping, binding, and/or precipitation as a result of the growth and metabolic activity of microorganisms, principally cyanophytes (blue-green algae) (Walter, 1976, p. 1).

Theoretical Interest in Shrub/Stromatolite Connection

- Is shrub formation generic?
  - Stromatolites & YNP shrubs from under water
  - NaCl shrubs form above water, presumably due to capillary action
- Detailed chemistry irrelevant
- Physical Ingredients of simple model
  - Sedimentation
  - Capillary action
  - Diffusion
- Simple model can capture qualitative and scaling features of real phenomena

DLA plus sedimentation yields stromatolitic structures in 2D (Grotzinger and Chan, unpublished)



Conclusions

- **Geobiological pattern formation at hot springs shows strong microbial partitioning, following geology and water chemistry**
- **Microbial cause of carbonate precipitation still unknown**
- **Indication that at least some of the geomorphology is generic**