Searching for Life on Earth and Mars

Carl Sagan Workshop
July 17, 2019

Dr. Ken Nealson
Dept. of Earth Science & Biological Sciences
University of Southern California

TAKE HOME LESSONS FROM YESTERDAY:

1. Prokaryotes are chemists – small cells; high S/V; diverse chemistry; “no” predation
   Activities leave their catalytic signatures everywhere

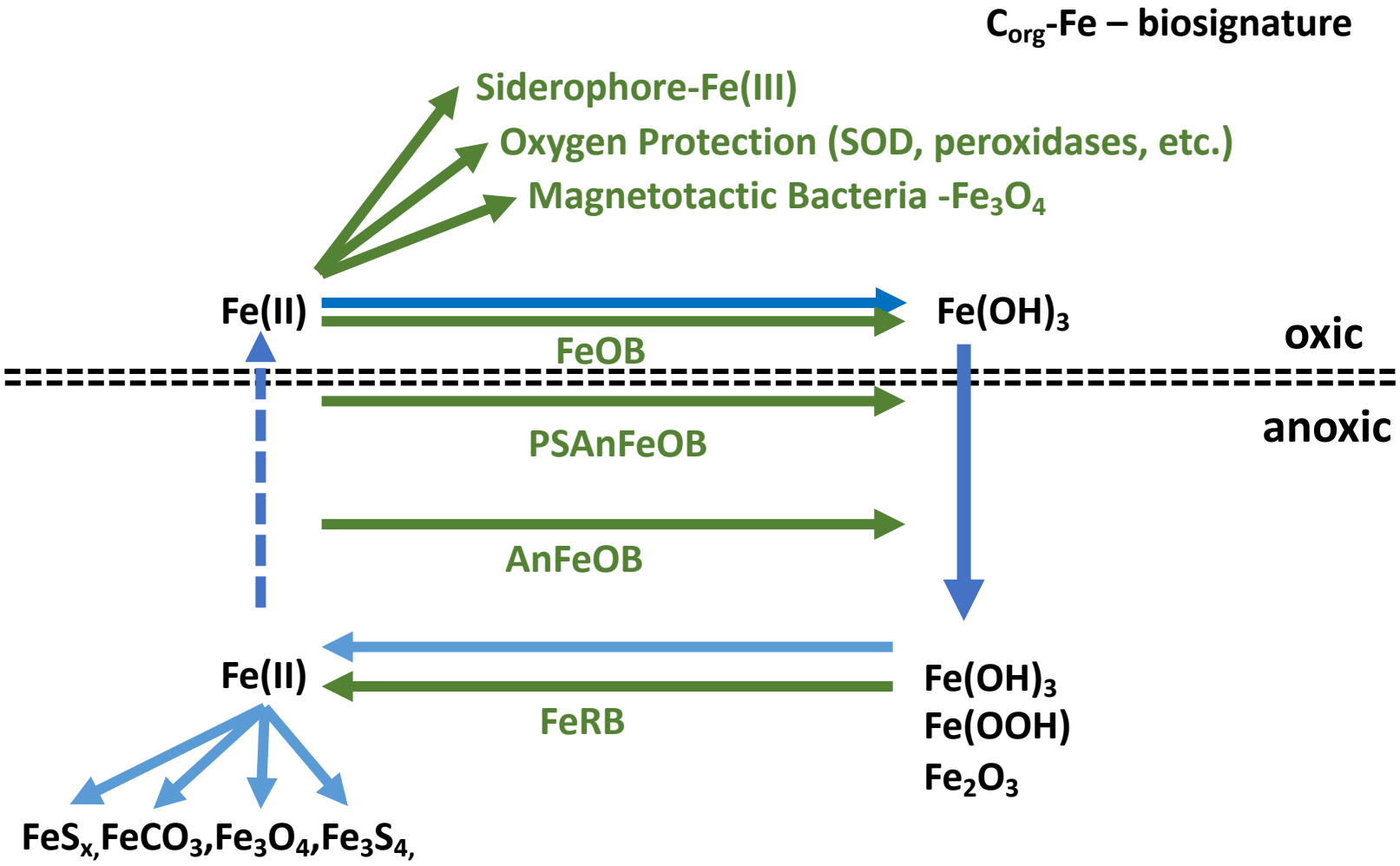
1. Eukaryotes are biologists – predator/prey; low S/V; ”simple” chemistry/ complex behaviour

2. Early life was anoxic, prokaryotic, slow growing, non-motile, communal

3. Oxygen changed everything

4. Prokaryotic life leaves its fingerprints everywhere – we just need to recognize them!

Life's "fingerprint" on the iron cycle:



After:
Stumm & Morgan, 1996
Aquatic Chemistry
Wiley & Sons, Inc.

One can do this for every elemental cycle on Earth !!

TODAY:

Strategy for life detection in samples from Earth or Mars

Can we develop a non-Earth-centric (NEC) method for life detection (LD)?

Comes from many discussions during my time at JPL -- MSR mission

Many efforts to detect life in extreme environments on Earth

Deep Subsurface – terrestrial & marine (dark, dry, low nutrients)

Anaerobic caves – CO_2/air interface (dark, dry, low nutrients)

Permafrost – cold, low liquid water

Acidic/hot springs – pH ~ 4, T ~ 90 C

Serpentinization sites (pH ~ 12, Eh -600 mV)

Result of many discussions with members of the Astrobiology group at JPL during the time I was there.

Sasha Tsapin
Michael Storrie-Lombardi
Gene McDonald
Pan Conrad
Rohit Bhartia
Bill Hug

Every Morning: Coffee and “can we develop a non-earthcentric method”

Why non-earthcentric ??

Does life have to be like earthly life? Why?

Could we detect it if it was different? How ?

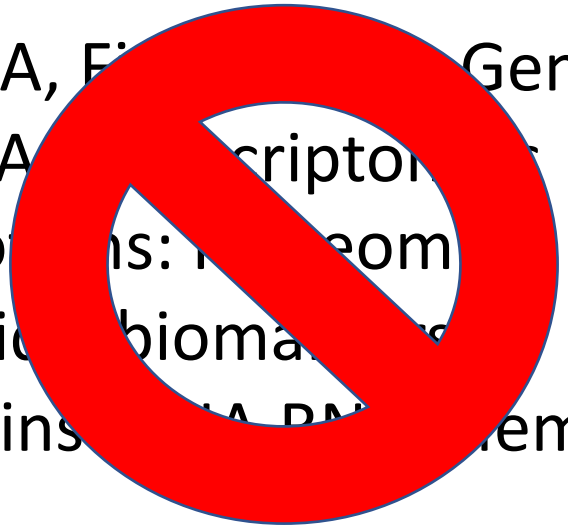
Could we (you) devise a non-EC strategy? (How?)

Which properties of life are universal?

Which properties of life can be quantified ?

RULES OF THE "NON-EARTHCENTRIC" (NEC) ROAD !!

Earth Centric = DNA, F… Genomics
RNA …cripto…
Pro…ns: P…eom… specific tests
Lipi… …bioma…s
Stains …A, RN… …embranes

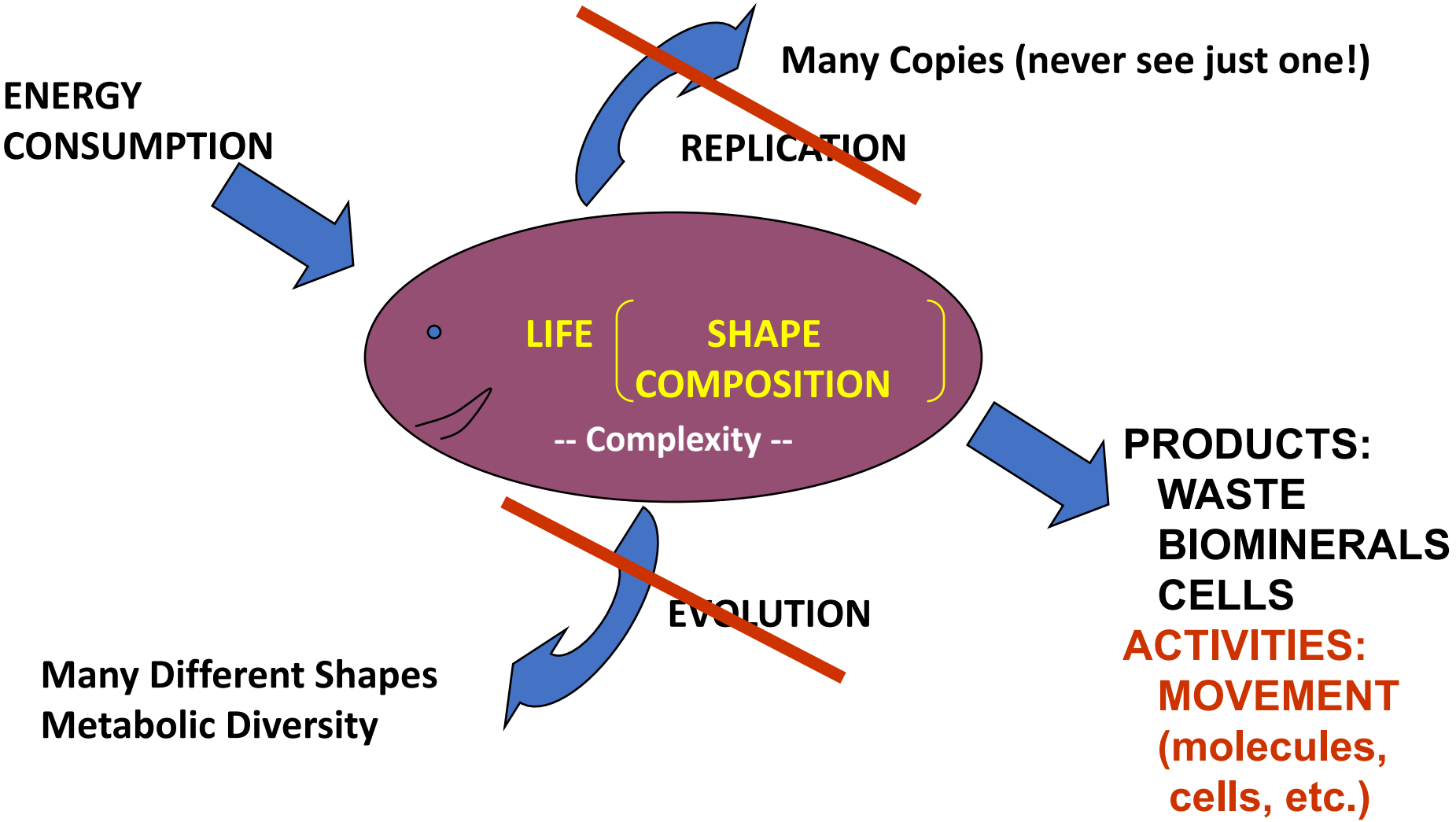


Non-Earth Centric = ??

What are the things that life HAS or DOES ??

1. Takes Energy from the environment (Thermodynamics)
2. Creates Waste products as it metabolizes
3. Should be able to alter rates of reactions (kinetics)
4. Some kind of complex and unique chemistry -- (composition)
5. Unique and complex chemistry – (function)
6. Reproduction (making copies)
7. Should be able to adapt and change over time (evolution)
8. Should be able to move – (non-random movement)
9. Will almost certainly alter the environment: atmospheric gases isotopic signatures of gases and solids: types and abundances of minerals

Fundamental Features of Life



Characteristics of Living Systems

Can we divine any Universal Features?:

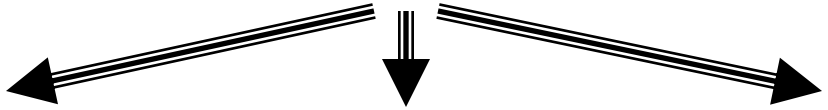
1. **Complexity of structure and function**
   cells and cell components
   metabolism and rapid reactions

2. **Non-equilibrium chemistry**
   cell components and make-up
   storage materials

3. **Observable environmental effects**
   establishment of chemical gradients and layers

4. **Non-random movement**

Approaches to Life Detection



Structure and Chemistry

A. Find the structures

B. Determine their Chemistry

- Elemental composition
- Chiral composition
- Isotope fractionation
- Complex molecules

Thermodynamics and Kinetics

A. Define the system

- Energy sources
- Electron donors
- Electron acceptors

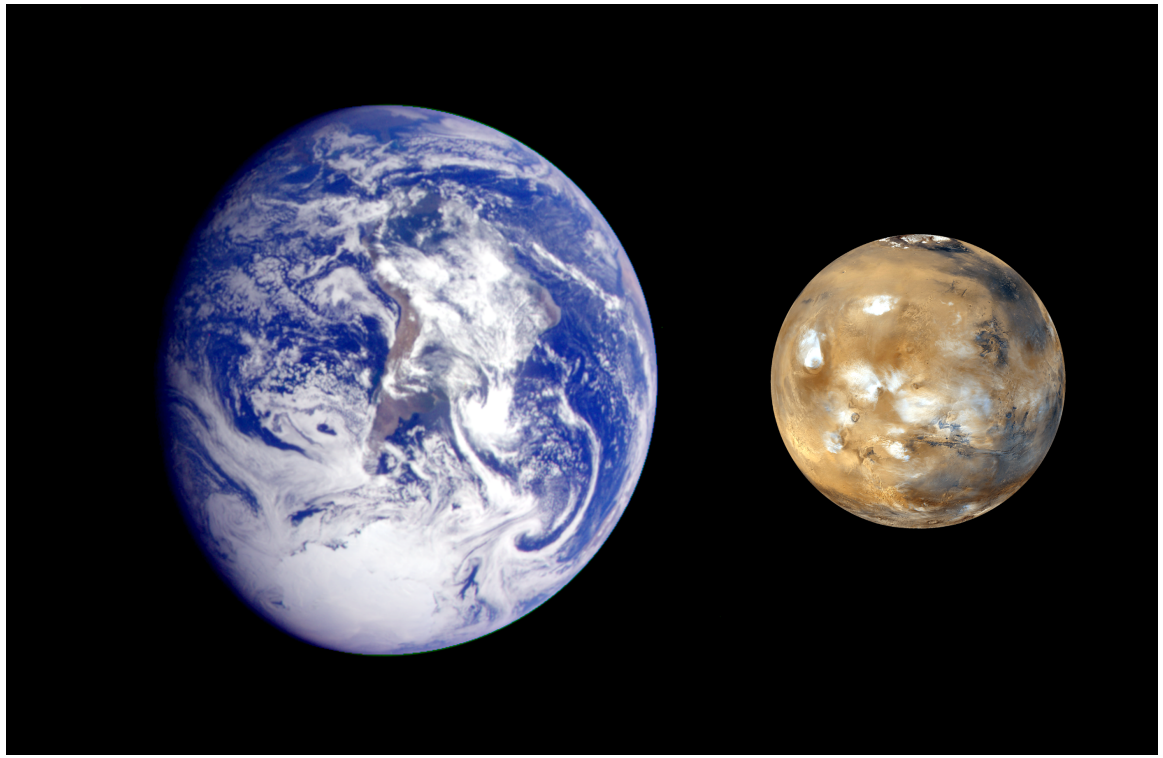
B. Identify temporal and spatial extents of energy disequilibria

- Layer formation
- Temporal disruptions

Non-Random Movement

A. Observe Movement

- Spatial scales
- Temporal scales
- Data treatment



What can we learn by studying the Earth, that will help us in the search for life on Mars?

1. Life is tough (extremophiles)
2. Life is tenacious (long survival times)
3. Life is metabolically diverse (it eats anything, it breathes anything !!)
4. When conditions get tough, life moves inside the rocks!
5. Life alters the rocks in ways that are recognizable

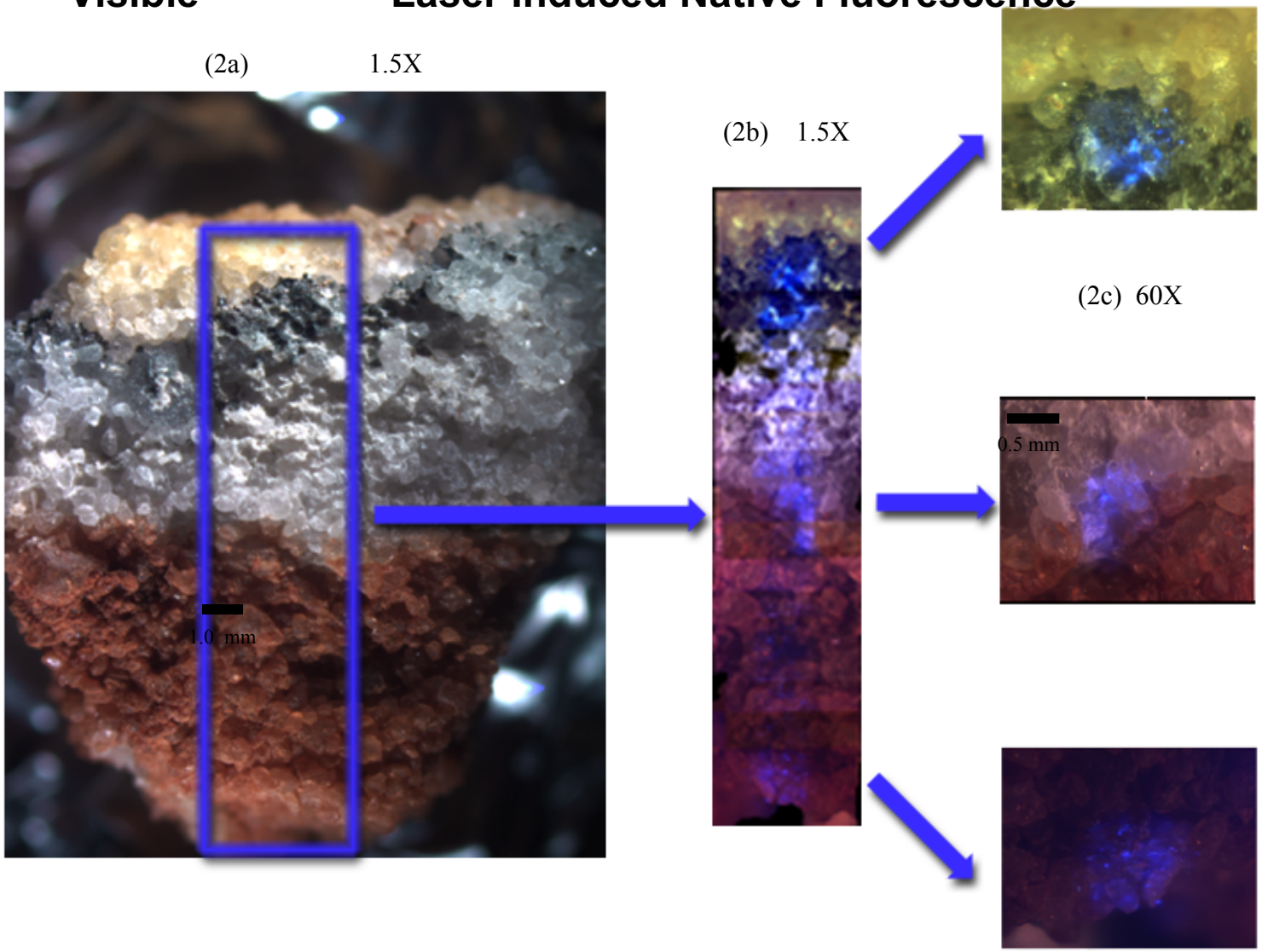
Life Detection Approach #1: Chemistry and Structure

- Look for Complexity
  - Spatial Scales
  - Temporal Scales
- Look for Structures
- Analyze Chemistry of Structures
- Statistical Analyses

(First find the Haystacks!!)
(Look there for the Needles !!)

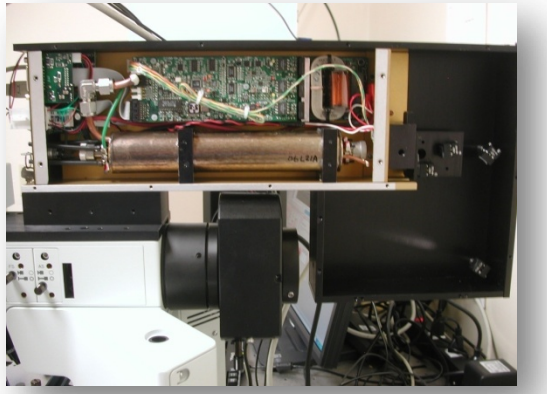
Antarctic Dry Valley Cryptoendolithic Community

Visible **Laser Induced Native Fluorescence**



Deep UV Native Fluorescence Microscope – Photon Systems; JPL; USC effort

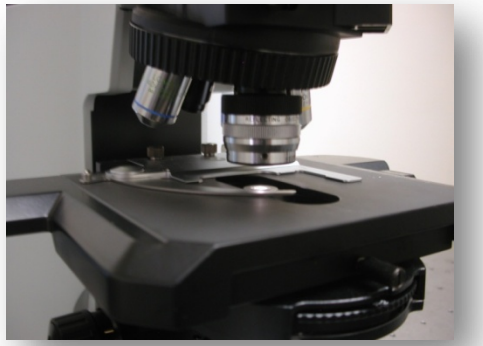
Deep UV Sensitive- EMCCD (Photon Counting)



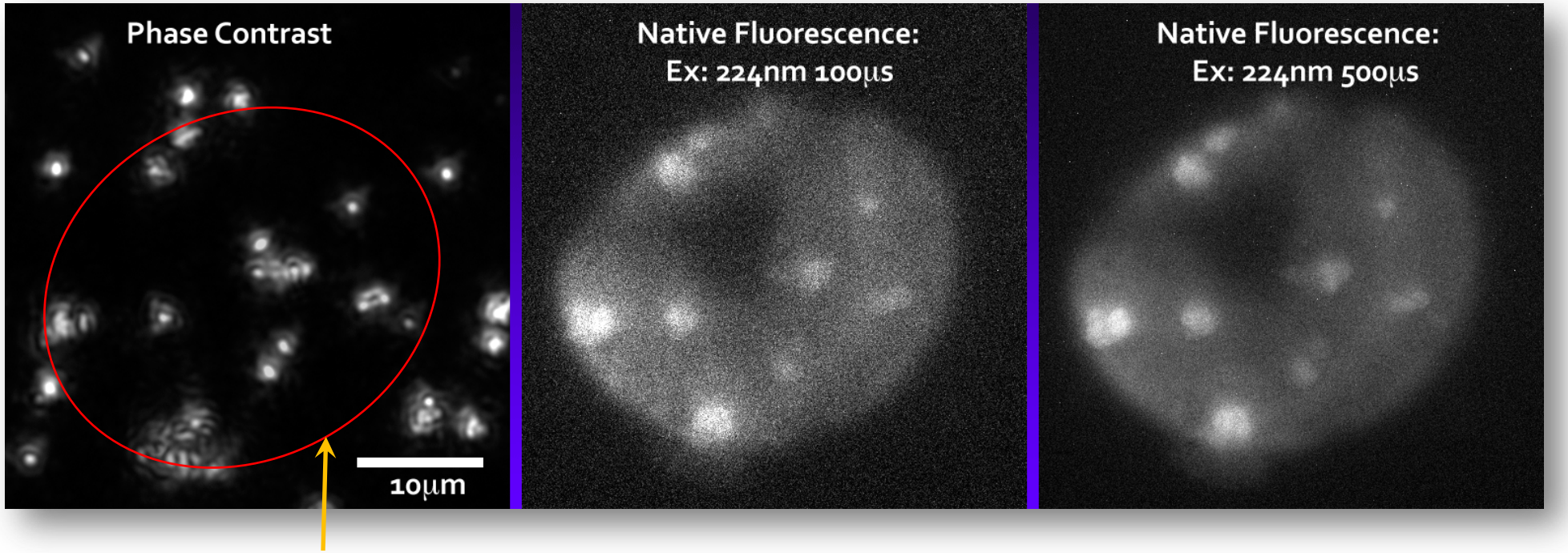
High Transmission UV Emission filters

Custom Deep UV Filter Block

Deep UV Reflective objective lens



Native Fluorescence of Shewanella MR1 Compare to transmitted light methods



Can this compete with standard microscopy? Phase contrast on a microscope slide – does pretty well (millisecond pulses)

Elemental Composition:

Redfield ratio indicates that all earthly life is composed of roughly the same elements.

C:N:P (100:15:1)
Also contains HOKN Ca Fe Mg

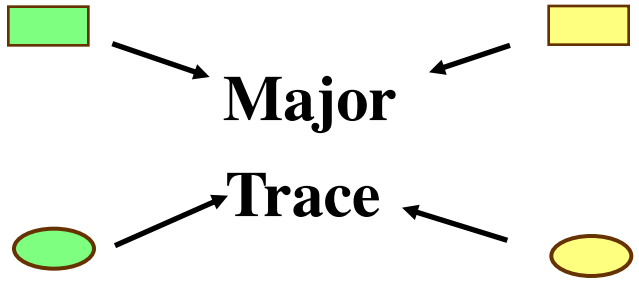
No mineral on the planet has this composition
Far too much nitrogen, and all the other things make it unique

Imagine that life on other planet would have same evolutionary trend – to be different from its environment !!

Components of Earth's Crust and Life

	Earth%	Life%	Ratio (L/E)
• Oxygen	50	50	~ 1
• Silicon	26	–	<.001
• Aluminum	7.5	–	<.001
• Hydrogen	0.5	7	~14
• Phosphorus	0.5	1	~2
• Nitrogen	0.05	6	~110
• Carbon	0.05	25	~500

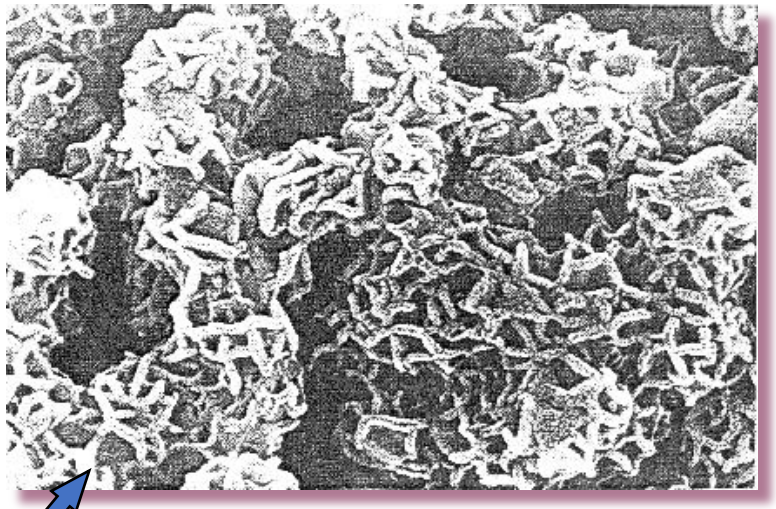
Comparisons



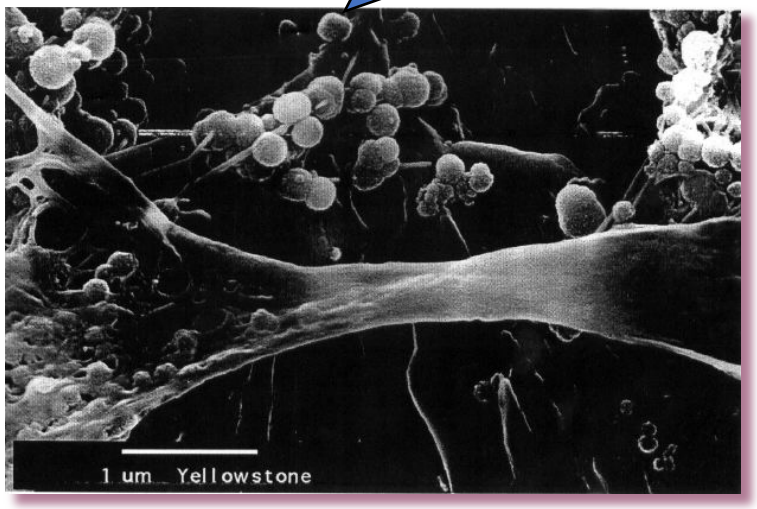
1 H 1.01																	2 He 4.00
3 Li 6.94	4 Be 9.01											5 B 10.81	6 C 12.01	7 N 14.01	8 O 16.00	9 F 19.00	10 Ne 20.18
11 Na 22.99	12 Mg 24.31											13 Al 26.98	14 Si 28.09	15 P 30.97	16 S 32.06	17 Cl 35.45	18 Ar 39.95
19 K 39.10	20 Ca 40.08	21 Sc 44.96	22 Ti 47.88	23 V 50.94	24 Cr 52.00	25 Mn 54.94	26 Fe 55.85	27 Co 58.93	28 Ni 58.69	29 Cu 63.55	30 Zn 65.39	31 Ga 69.72	32 Ge 72.59	33 As 74.92	34 Se 78.96	35 Br 79.90	36 Kr 83.80
37 Rb 85.47	38 Sr 87.62	39 Y 88.91	40 Zr 91.22	41 Nb 92.91	42 Mo 95.94	43 Tc (98)	44 Ru 101.07	45 Rh 102.91	46 Pd 106.42	47 Ag 107.87	48 Cd 112.41	49 In 114.82	50 Sn 118.71	51 Sb 121.75	52 Te 127.60	53 I 126.91	54 Xe 131.29
55 Cs 132.91	56 Ba 137.33	57 La 138.91	72 Hf 178.49	73 Ta 180.95	74 W 183.85	75 Re 186.21	76 Os 190.2	77 Ir 192.22	78 Pt 195.08	79 Au 196.97	80 Hg 200.59	81 Tl 204.38	82 Pb 207.2	83 Bi 208.98	84 Po (209)	85 At (210)	86 Rn (222)
87 Fr (223)	88 Ra 226.03	89 Ac 227.03	104 Rf (261)	105 Ha (262)	106 Sg (263)	107 Ns (262)	108 Hs (266)	109 Mt (266)	110 Uun (269)	111 Uuu (272)	112 Uub (277)						

58 Ce 140.12	59 Pr 140.91	60 Nd 144.24	61 Pm (145)	62 Sm 150.36	63 Eu 151.96	64 Gd 157.25	65 Tb 158.93	66 Dy 162.50	67 Ho 164.93	68 Er 167.26	69 Tm 168.93	70 Yb 173.04	71 Lu 174.97
90 Th 232.03	91 Pa 231.04	92 U 238.03	93 Np 237.05	94 Pu (244)	95 Am (243)	96 Cm (247)	97 Bk (247)	98 Cf (251)	99 Es (252)	100 Fm (257)	101 Md (258)	102 No (259)	103 Lr (260)

Find the structures that look like life!

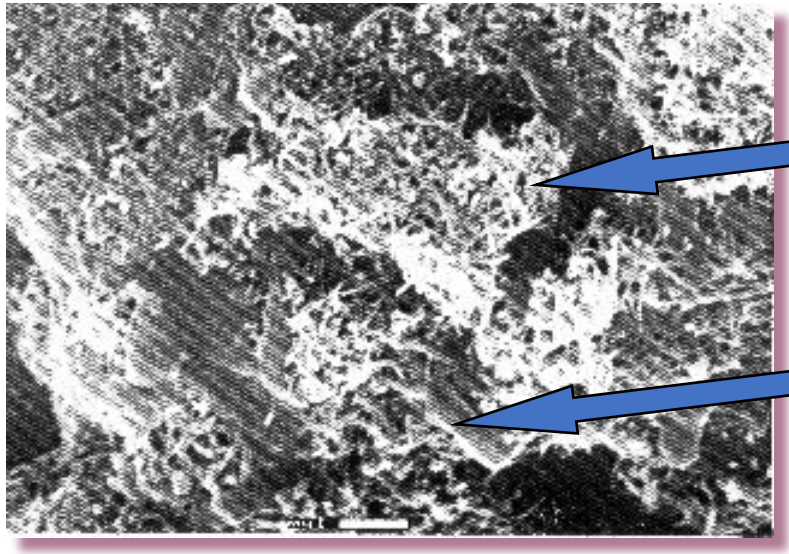


(Fe,O)



(Ca,F)

Elemental Analysis via Nano-SIMS (Sec. Ionization Mass spectrom.)



(Mn, O)

(C,N,P,S,K,Ca Fe,Ni,Mn,etc)

Composition and Distribution

Composition:

Thermodynamics predicts abundances

Life gives a totally unpredicted distribution

Examples:

amino acids – number and amounts -- Easy

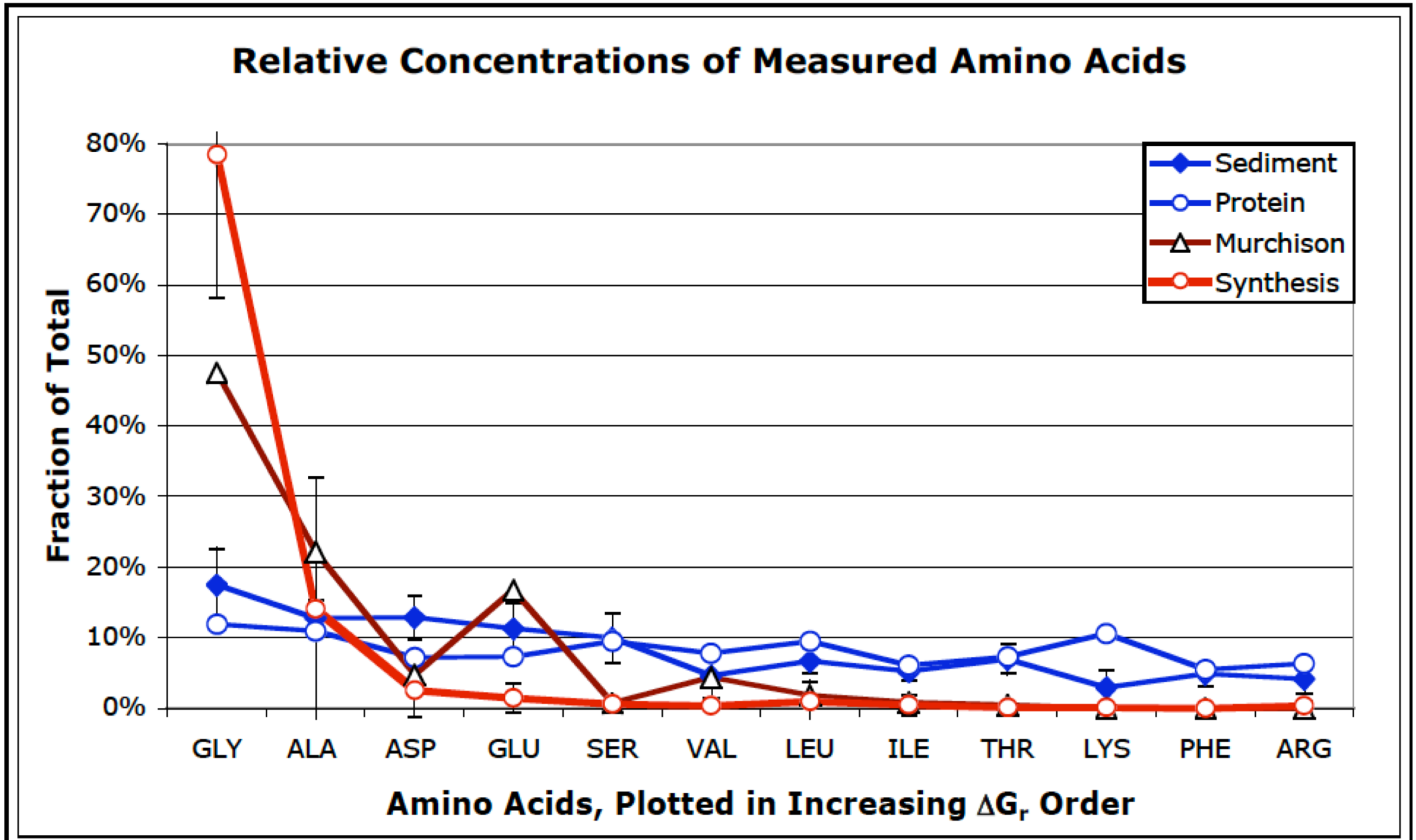
chirality of amino acids Difficult

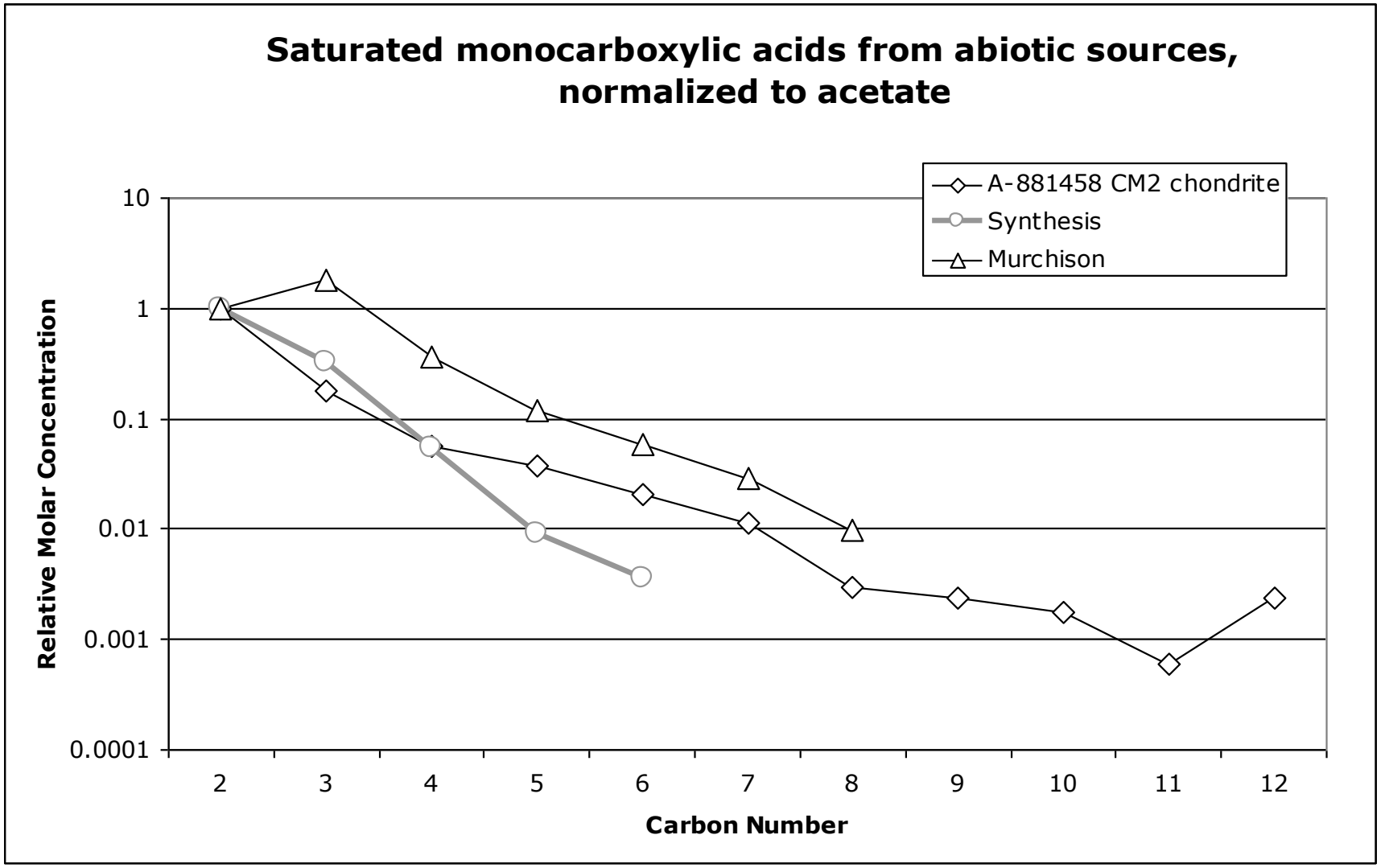
sugars – number and amounts -- Easy

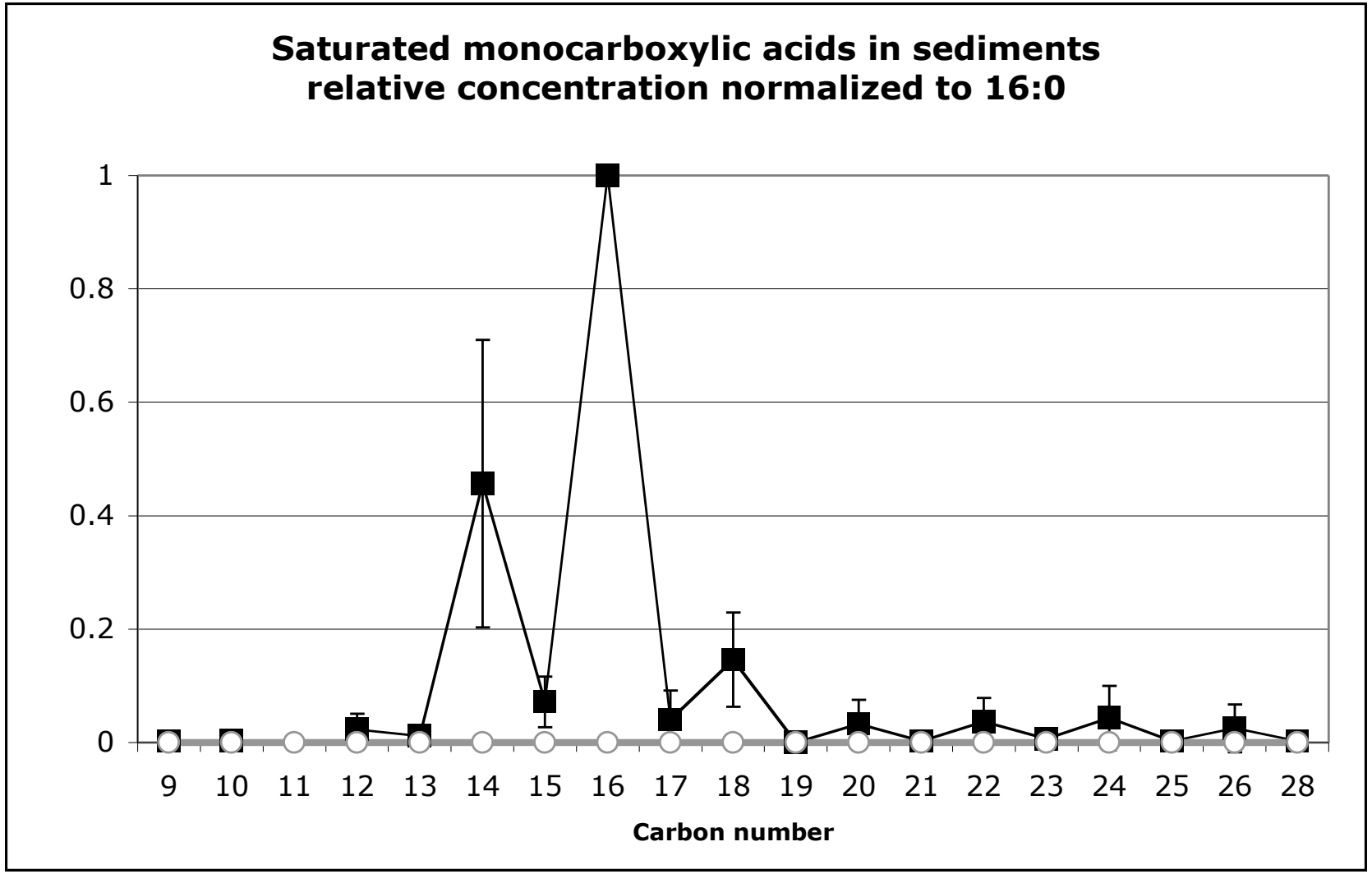
chirality of sugars -- Difficult

Lipids – fatty acid numbers and amounts -- Easy

Proteins – totally unpredicted !! Data Base: all L, only 20 !

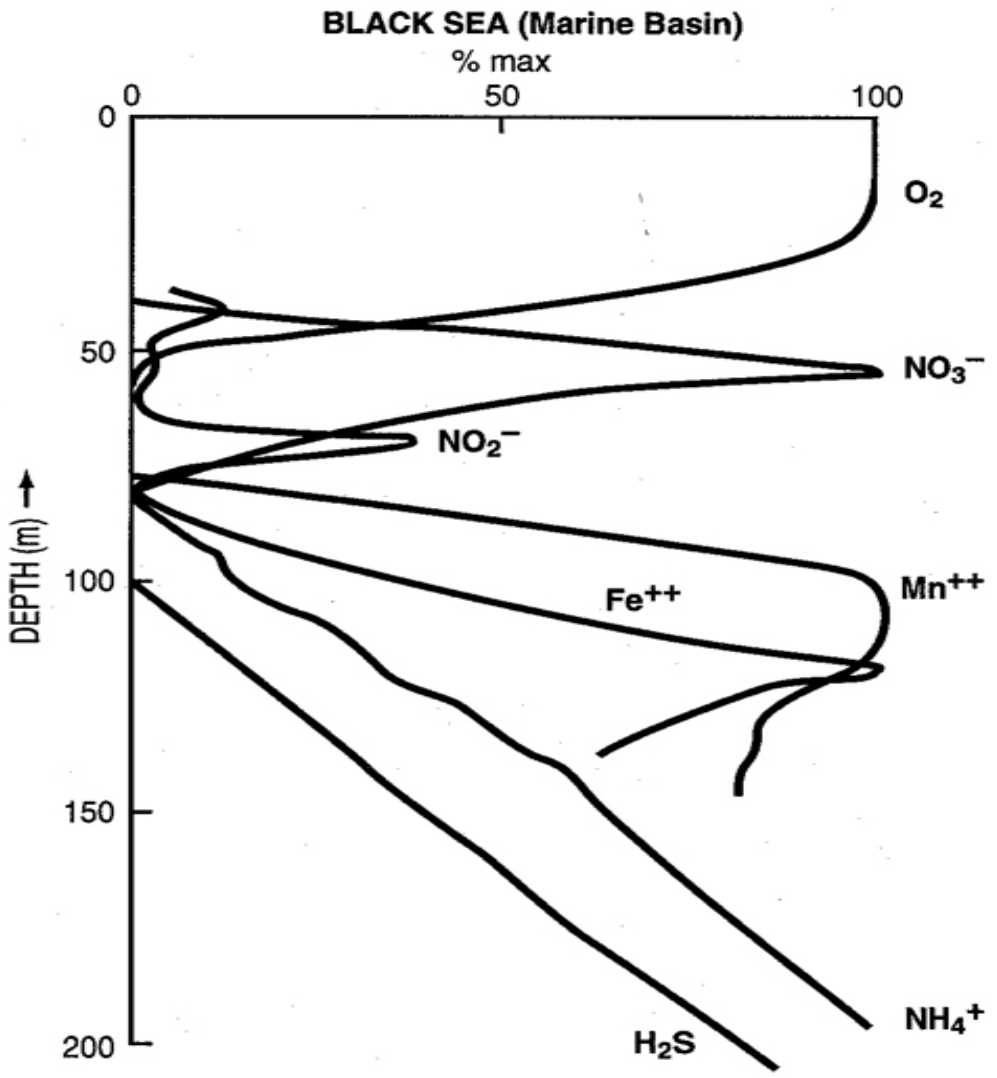

Relative Concentrations of Measured Amino Acids
Fraction of Total
80%
70%
60%
50%
40%
30%
20%
10%
0%
Sediment
Protein
Murchison
Synthesis
GLY
ALA
ASP
GLU
SER
VAL
LEU
ILE
THR
LYS
PHE
ARG
Amino Acids, Plotted in Increasing ΔG$_r$ Order


Saturated monocarboxylic acids from abiotic sources, normalized to acetate
A-881458 CM2 chondrite
Synthesis
Murchison
Relative Molar Concentration
10
1
0.1
0.01
0.001
0.0001
2
3
4
5
6
7
8
9
10
11
12
Carbon Number


Saturated monocarboxylic acids in sediments
relative concentration normalized to 16:0
1
0.8
0.6
0.4
0.2
0
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
28
Carbon number

Life Detection Approach #2

- Look for activities
  - nutrient uptake
  - product excretion
- Use thermodynamic logic
- Measure kinetics
  - variety of temporal scales needed



Biogeochemical Processes

Oxygen Diffusion from Atmosphere

Oxygenic Photosynthesis
Oxygen Respiration

Nitrification

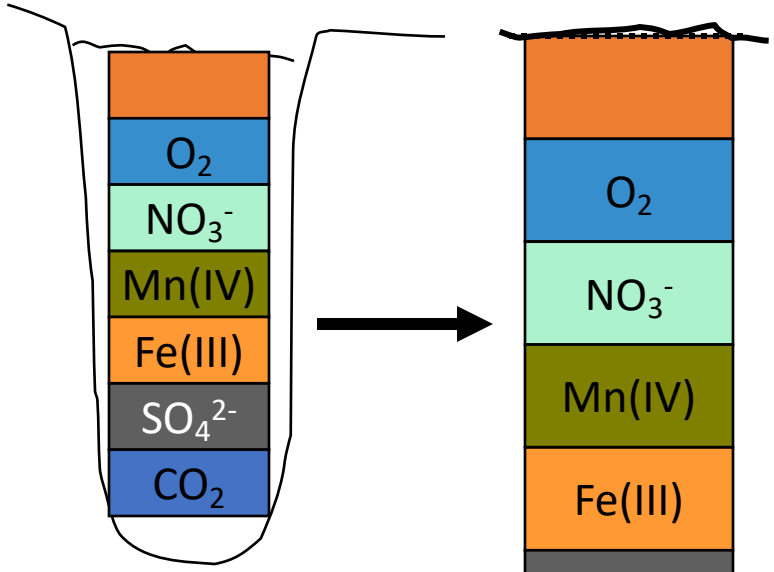
Denitrification

Mn oxidation
Mn reduction
Fe oxidation

Fe reduction
Sulfide oxidation

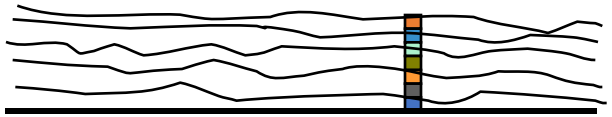
Sulfate reduction

Occurrences of LMCs

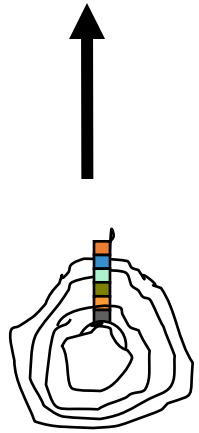


Stratified Lakes And Marine Basins (meters)

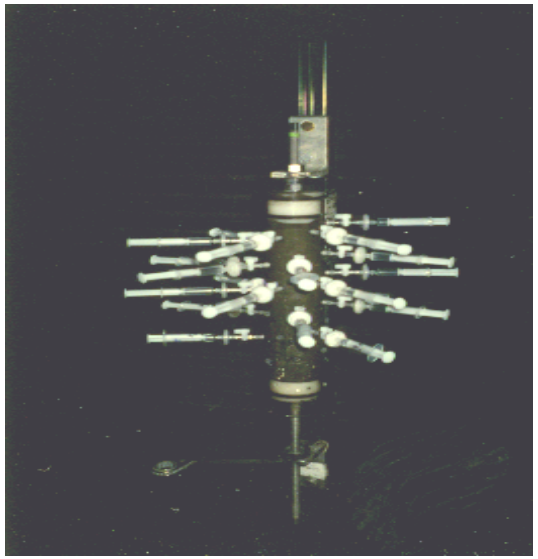
Water Saturated Sediments and Mat Systems (cm – mms)

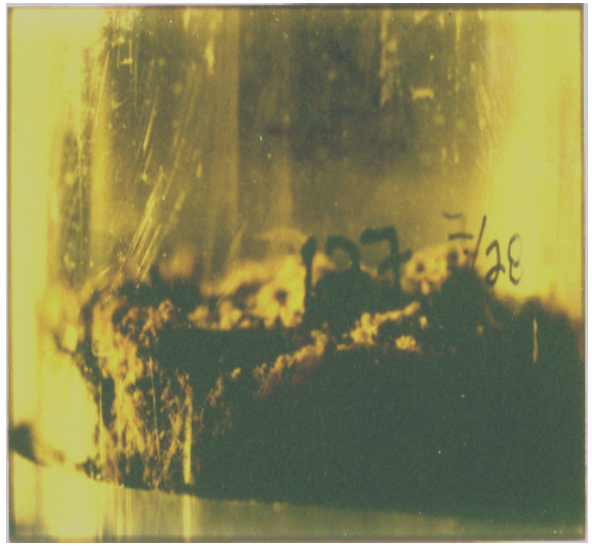


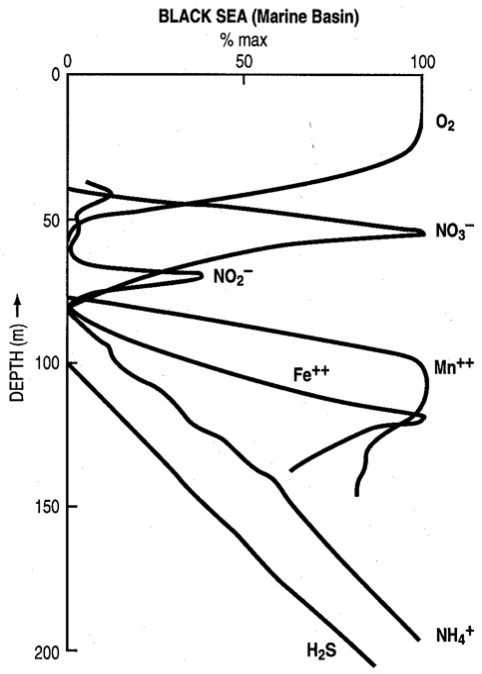
Biofilms -- micrometers

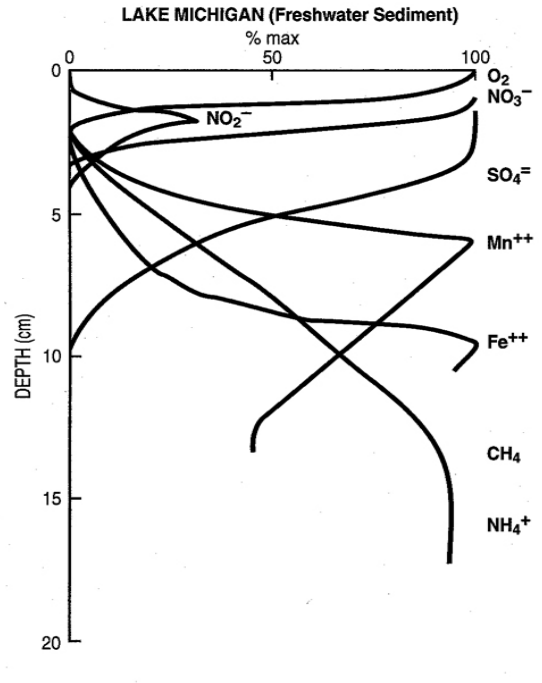


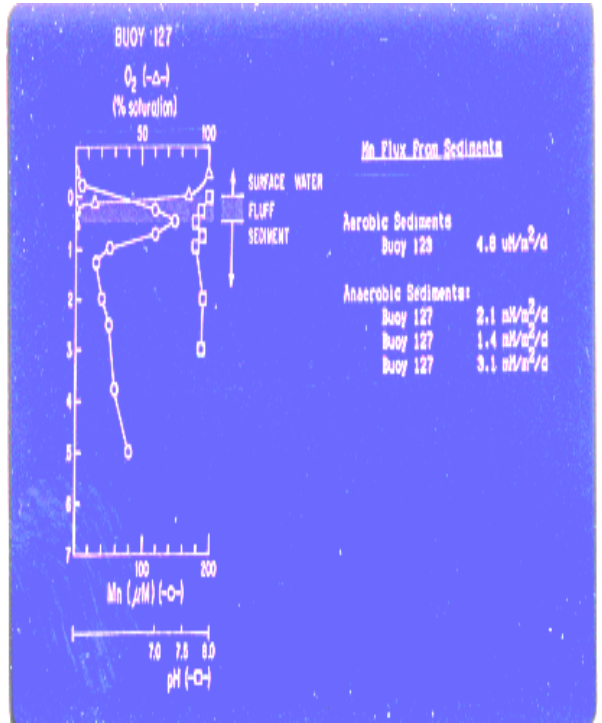
Particles in Unsaturated Sediments (mm - micrometers)

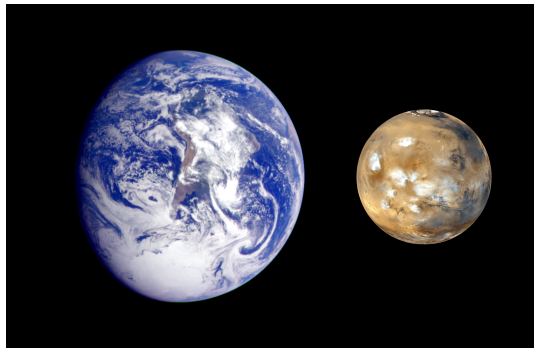





BLACK SEA (Marine Basin)
% max
0
50
100
DEPTH (m)
0
50
100
150
200
O_2
NO_3^-
NO_2^-
Fe^{++}
Mn^{++}
H_2S
NH_4^+


LAKE MICHIGAN (Freshwater Sediment)
% max
0
50
100
DEPTH (cm)
0
5
10
15
20
O_2
NO_3^-
NO_2^-
$SO_4^=$
Mn^{++}
Fe^{++}
CH_4
NH_4^+


BUOY 127
O_2 (-o-)
(% saturation)
50
100
SURFACE WATER
FLUFF
SEDIMENT
Mn Flux From Sediments
Aerobic Sediments
Buoy 123
4.8 mM/m²/d
Anaerobic Sediments:
Buoy 127
2.1 mM/m²/d
Buoy 127
1.4 mM/m²/d
Buoy 127
3.1 mM/m²/d
100
200
Mn (μM) (-o-)
7.0
7.5
8.0
pH (-□-)



To Summarize:

Life leaves distinct kinetic signatures
Prokaryotic life is responsible for most of these

Expression of metabolic diversity

Very strong imprint on the Earth
Should be recognizable on any planet if life is there!

Article

Design and preliminary verifications of an instrument to study the evolution of electrochemical gradients

Radu Popa [1], Vily M. Cimpoiasu [2,*], Faustin Radulescu [3] and Kenneth H. Nealson [4]

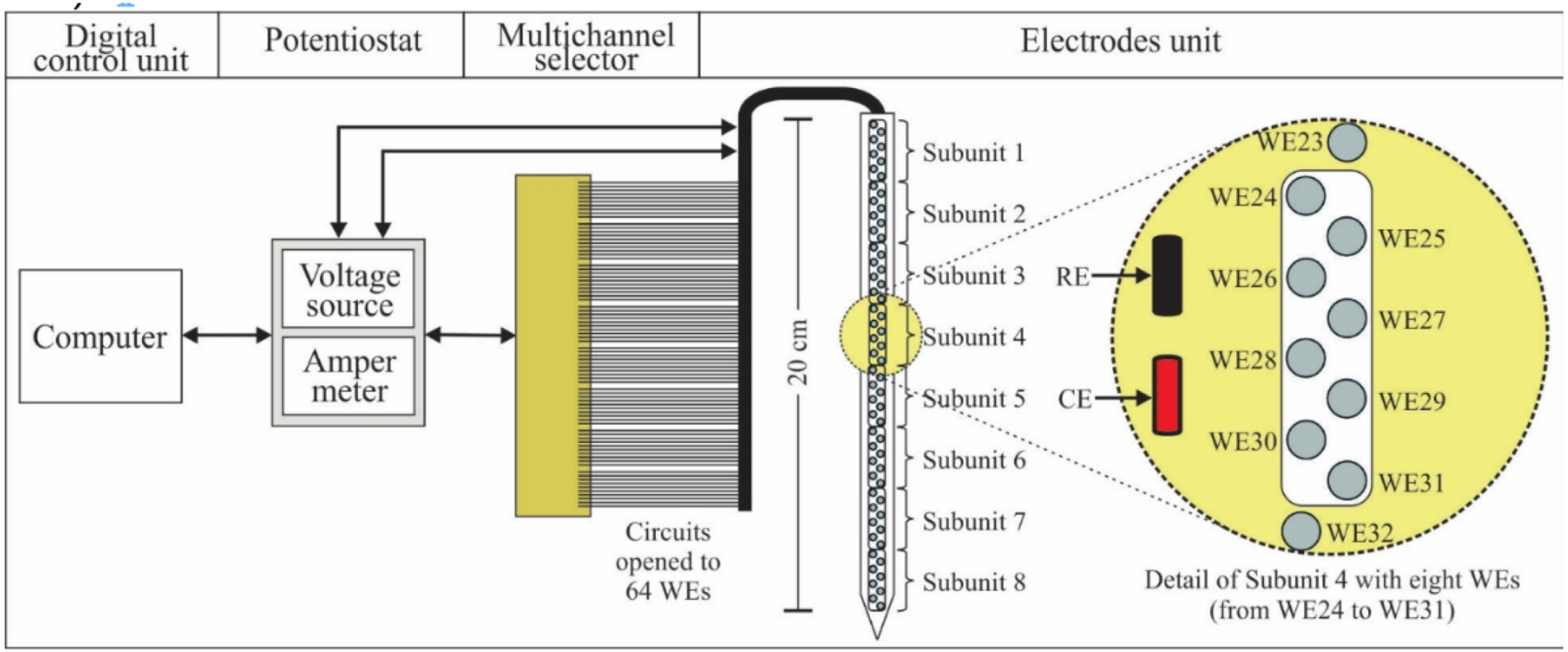
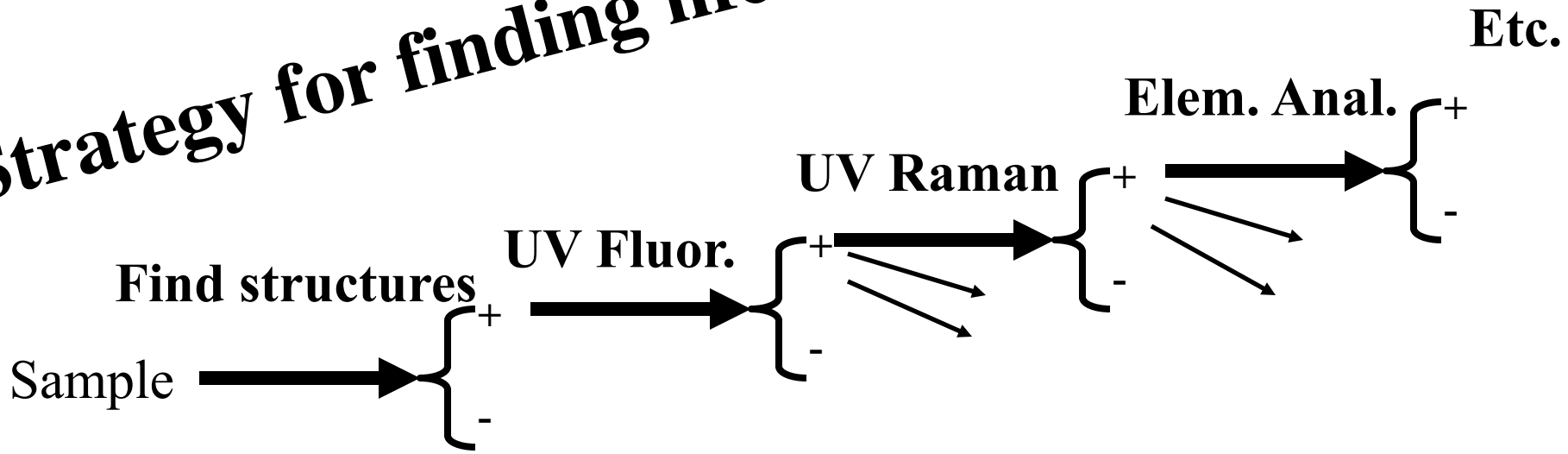


Figure 2. Architecture of a SPEAR instrument with 64 working electrodes (WEs). This probe has eight subunits with eight WEs each.

Strategy for finding life in the environment !!



Physics + Chemistry + Probabilistics = Life Detection
Smart but uneducated computers needed !!
Decision making systems must be enabled !!
ASK SIMPLE QUESTIONS !!

KEN'S LAWS OF LIFE DETECTION

1. **Know your planet**
   physics, chemistry, geology
   atmosphere and lithosphere
   energy sources and oxidants
   (IF NO LIFE, LEARN WHY!!)
2. **Use non-Earth-centric approaches**
   physics, chemistry, geology, statistics
   look for general features (IF LIFE, DON'T MISS IT !!)
3. **Keep an open mind**
   life may be quite different from what we know
   energy, oxidants, gravity, etc. (THINK FREELY !!)