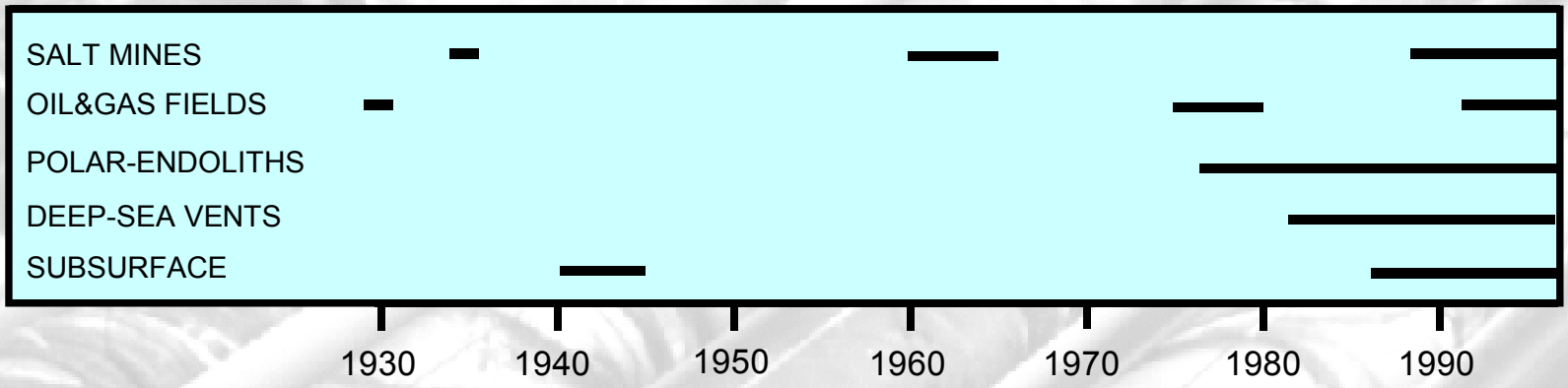
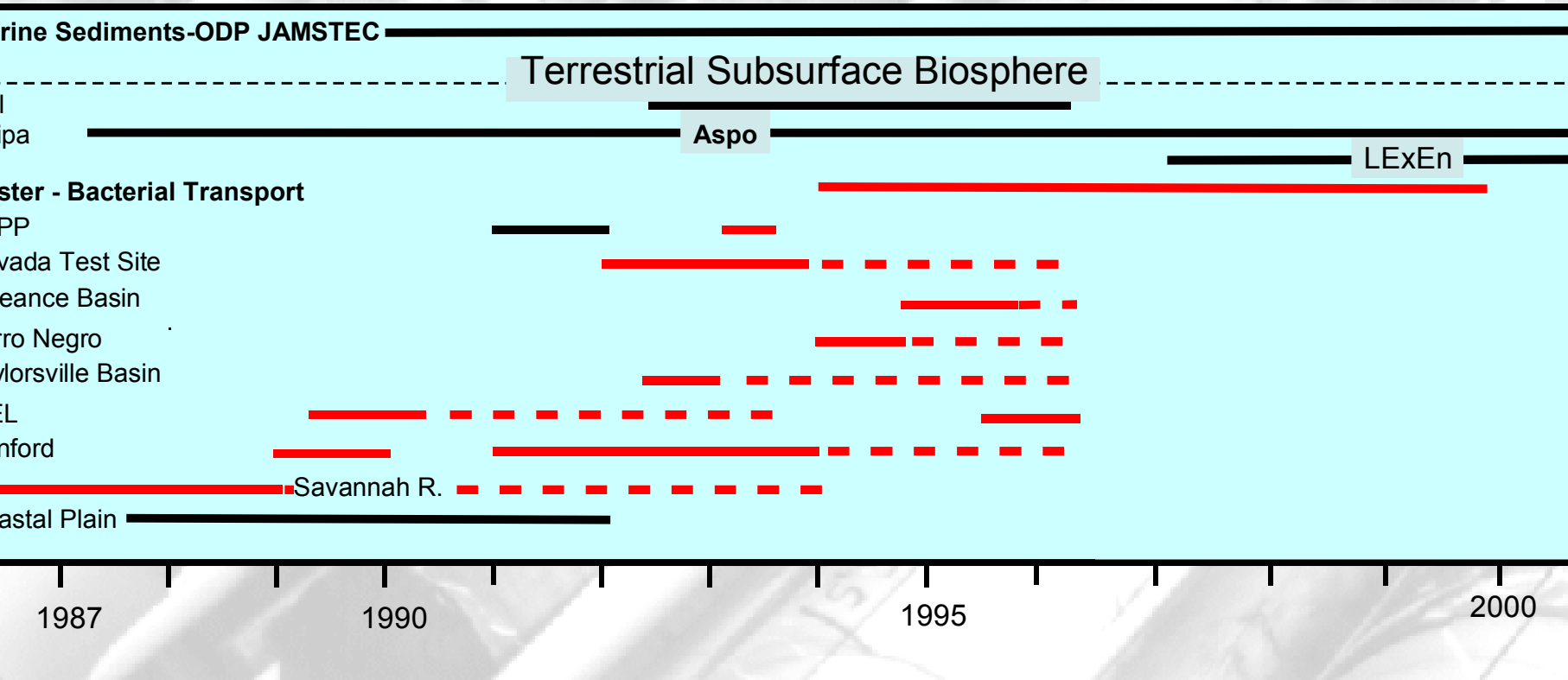
Deep Subsurface Microorganisms in Tectonically Active Environments:

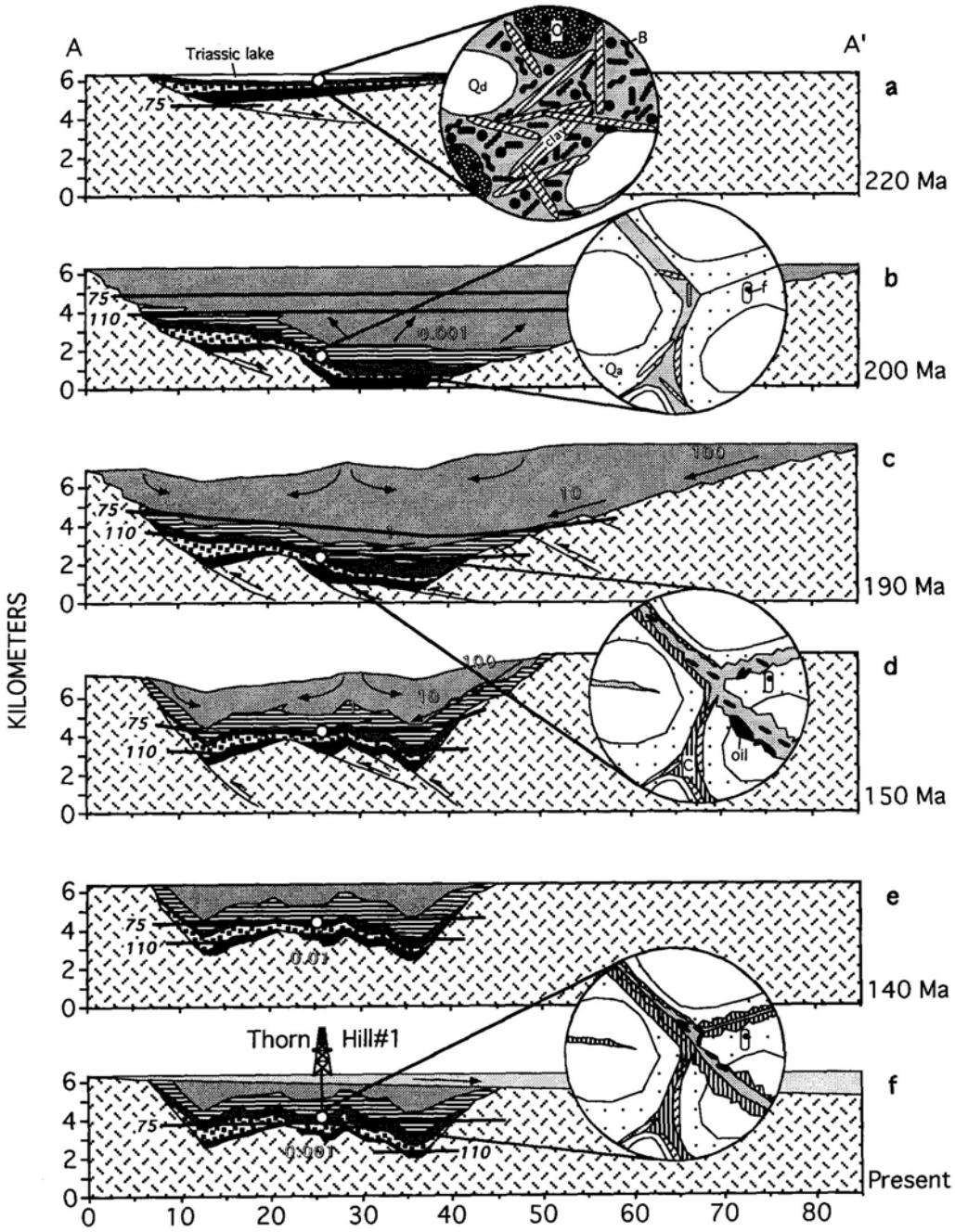
A New Frontier?

CHRONOLOGY OF SUBSURFACE MICROBIOLOGY





Taylorsville Basin First Deep Subsurface Microbial Investigation



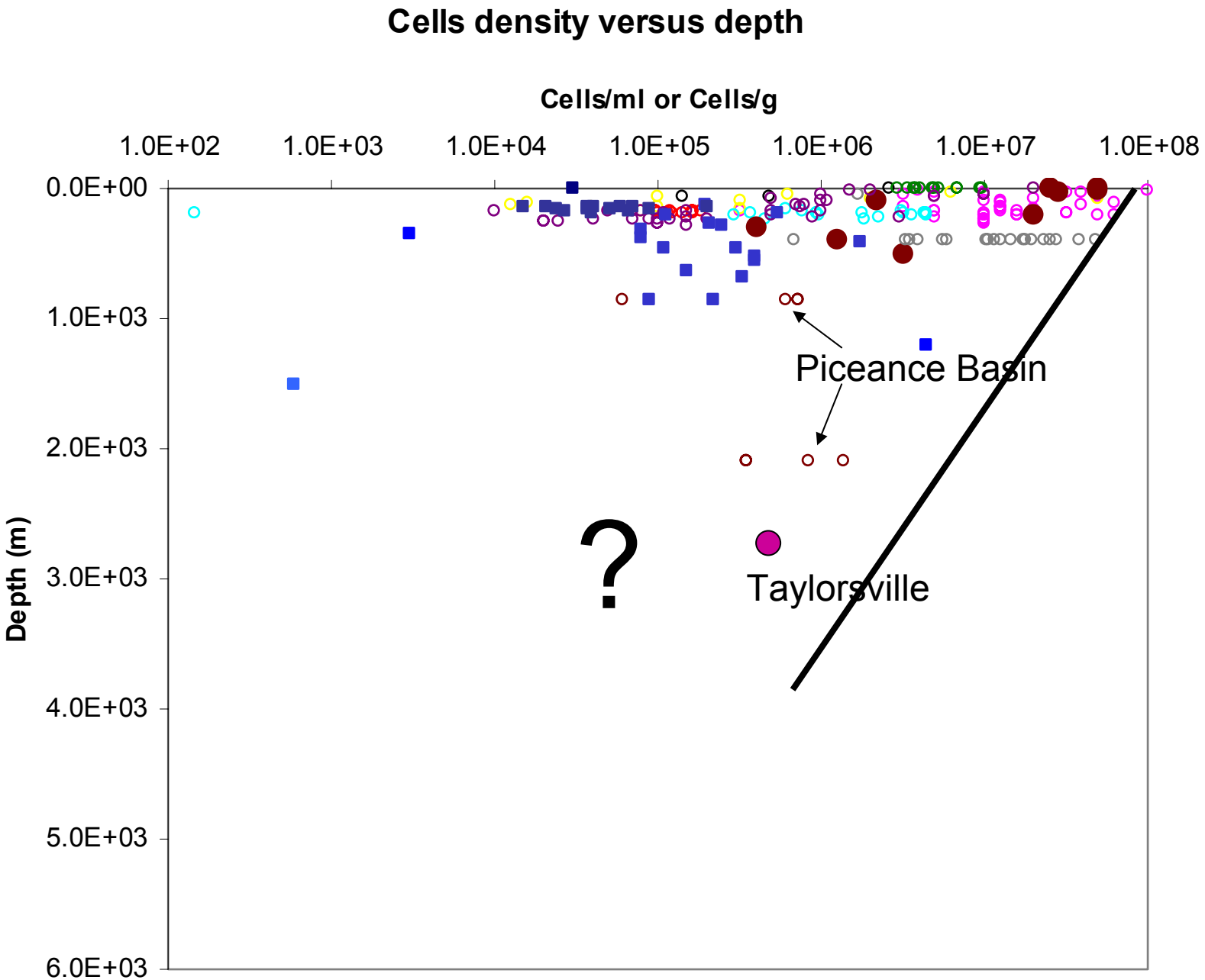
Microbial Origins

1. Growth in Triassic lacustrine sediments
2. Burial, heating and sterilization at T > 150°C.
3. Uplift, meteoric fluid infiltration, microbial transport during Jurassic tectonism.
4. Diminishing fluid flow and permeability with increasing cementation.
5. On lap of coastal marine sand and mud hydrological ly isolates basin.
6. Deep coring recovers anaerobic microorganisms.

Tectogenetic Origin for Deep Subsurface Microorganisms (Tseng et al. 1996)

Orogenic uplift and cooling leads to:

1. Increased, topographically driven, fluid flow increasing microbial migration.
2. Enhanced hydraulic conductivity due to fracturing increasing microbial migration.
3. Low fluid salinity from meteoric recharge enhances microbial migration.
4. High nutrient availability in sterilized rock promotes microbial growth and hence migration during colonization.


Cells density versus depth
Cells/ml or Cells/g
1.0E+02
1.0E+03
1.0E+04
1.0E+05
1.0E+06
1.0E+07
1.0E+08
0.0E+00
1.0E+03
2.0E+03
3.0E+03
4.0E+03
5.0E+03
6.0E+03
Depth (m)
Piceance Basin
?
Taylorsville

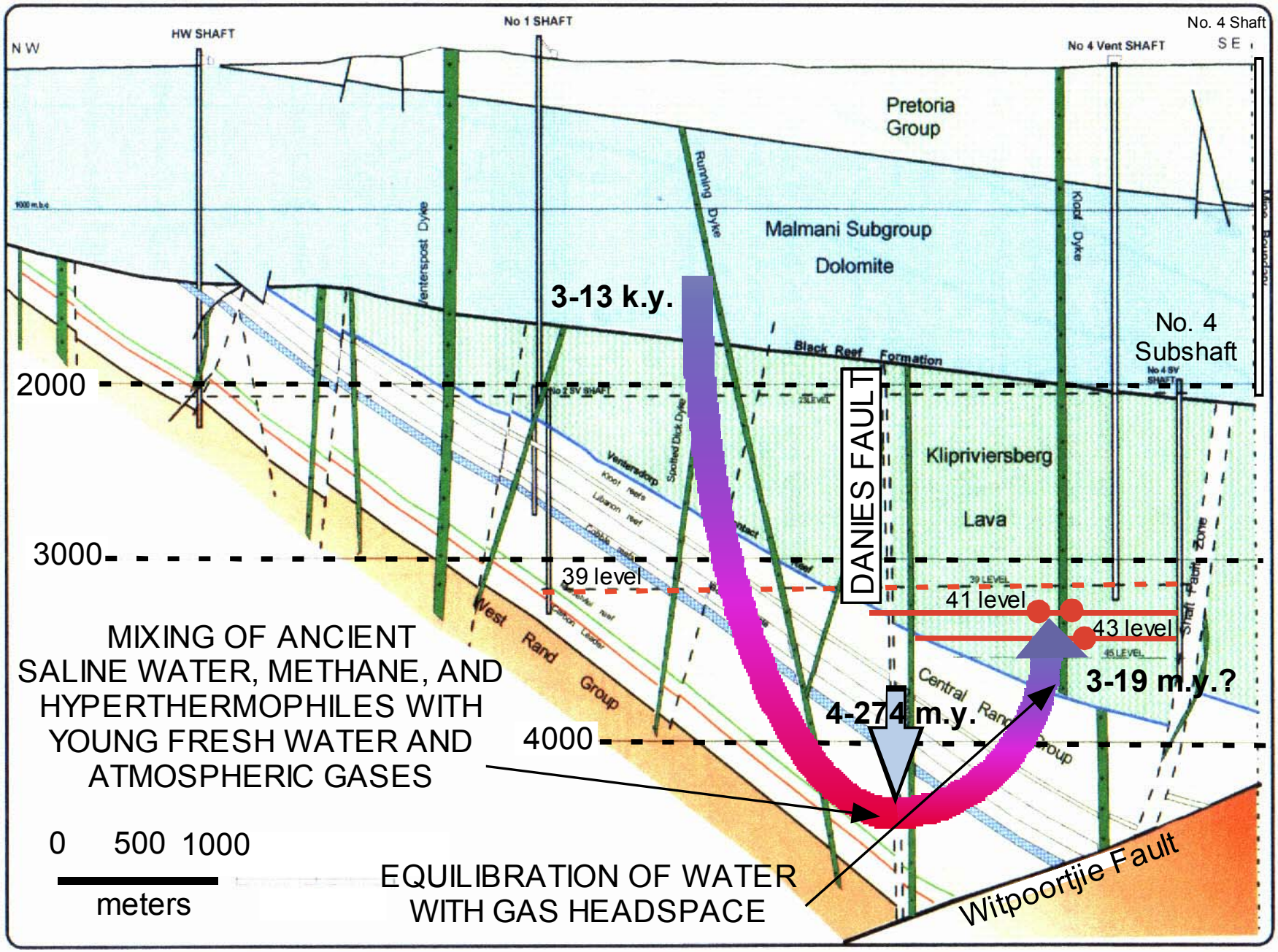
Two Questions

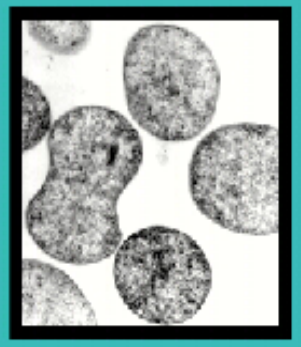
1. How can deep subsurface microbial communities survive tens or hundreds of millions of years separated from the photosphere?
2. Are the deep subsurface microbial and nutrient fluxes greater in tectonically active environments than in quiescent crustal or marine sedimentary environments?

VITWATERSRAND DEEP MICROBIOLOGY PROJECT

A WINDOW INTO THE EXTREME ENVIRONMENT OF THE DEEP SUBSURFACE

SUPPORTED BY GRANTS FROM:
THE LEXEN PROGRAM--NATIONAL SCIENCE FOUNDATION
THE NATIONAL GEOGRAPHIC SOCIETY


BANK COMPARTMENT
VENTERSPOST COMPARTMENT
NW
HW SHAFT
No 1 SHAFT
No 4 Vent SHAFT
No. 4 Shaft
SE
Pretoria Group
Malmani Subgroup
Dolomite
Venterspost Dyke
Running Dyke
Kloof Dyke
3-13 k.y.
No. 4 Subshaft
Black Reef Formation
2000
3000
4000
DANIES FAULT
Klipriviersberg Lava
39 level
41 level
43 level
West Rand Group
Central Rand Group
3-19 m.y.?
4-274 m.y.
MIXING OF ANCIENT SALINE WATER, METHANE, AND HYPERTHERMOPHILES WITH YOUNG FRESH WATER AND ATMOSPHERIC GASES
0 500 1000
meters
EQUILIBRATION OF WATER WITH GAS HEADSPACE
Witpoortjie Fault



PYROCOCCUS "FiREBALL" IN MINE FISSURE WATER

A Biological tracer of upwelling geothermal water?

Fissure Water Characteristics

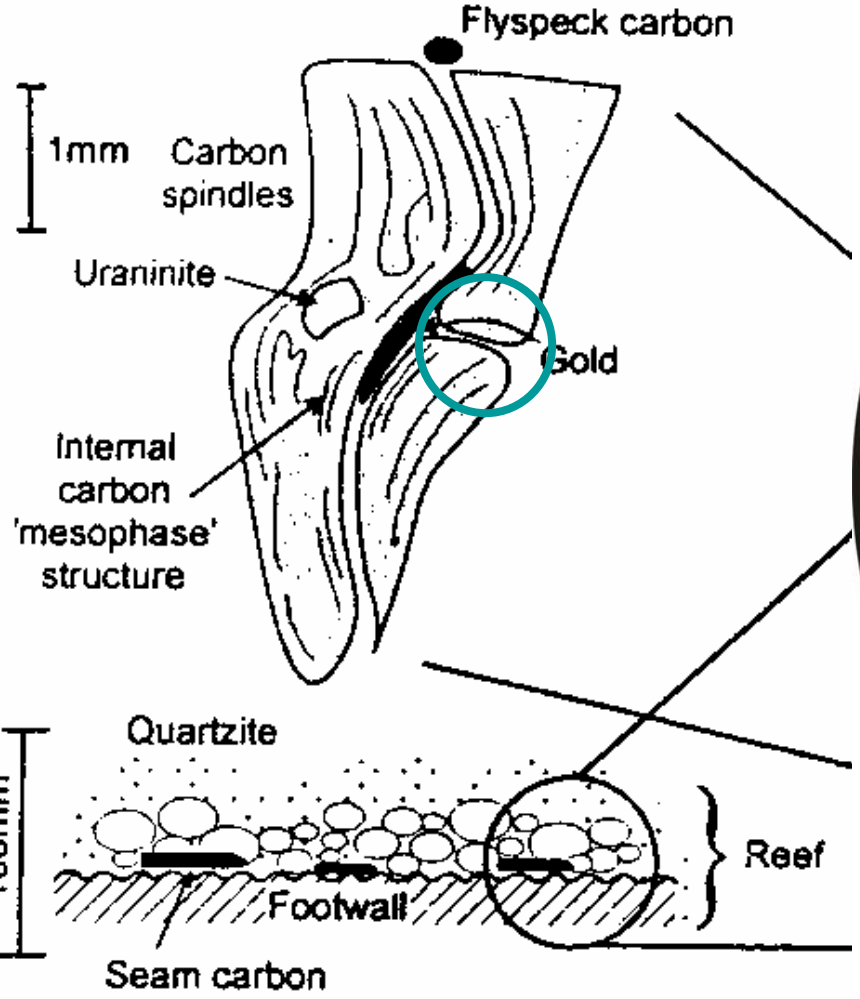
- Anerobic and microaerophilic
- 35 - 60°C

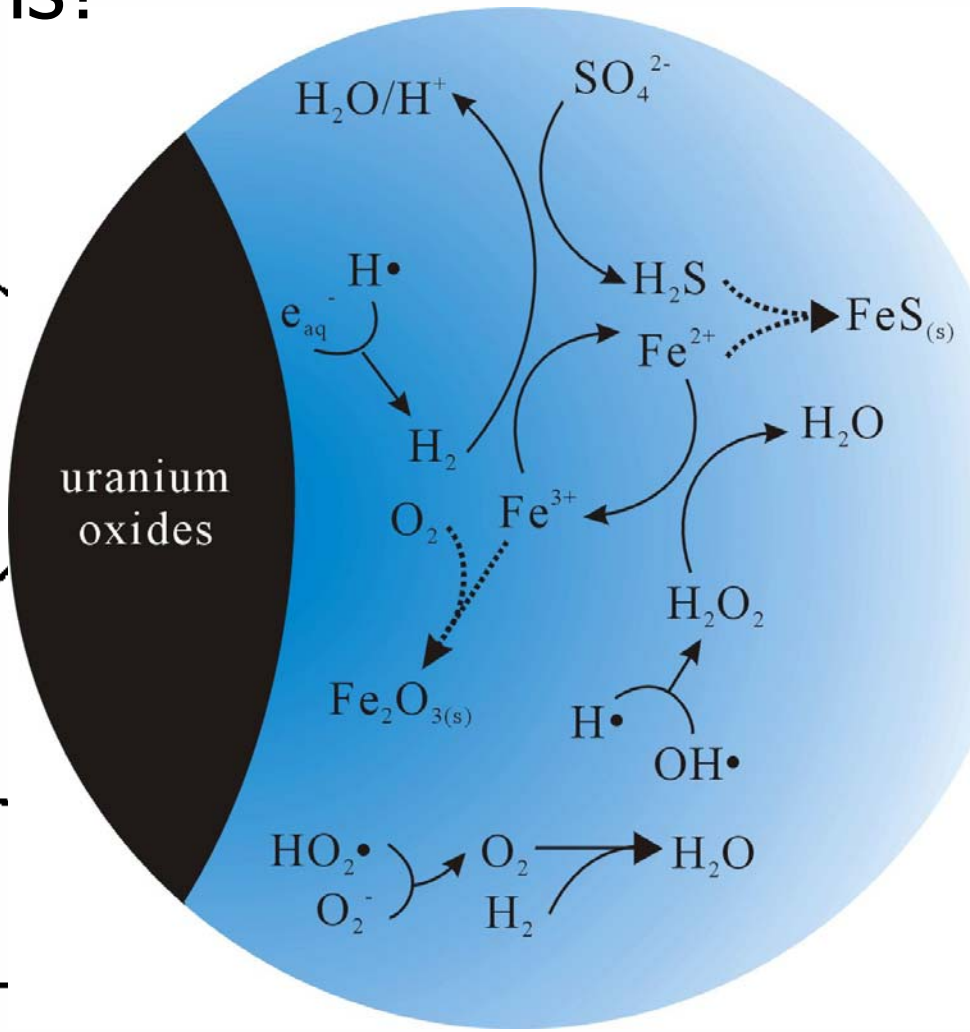
P. abysii Characteristics

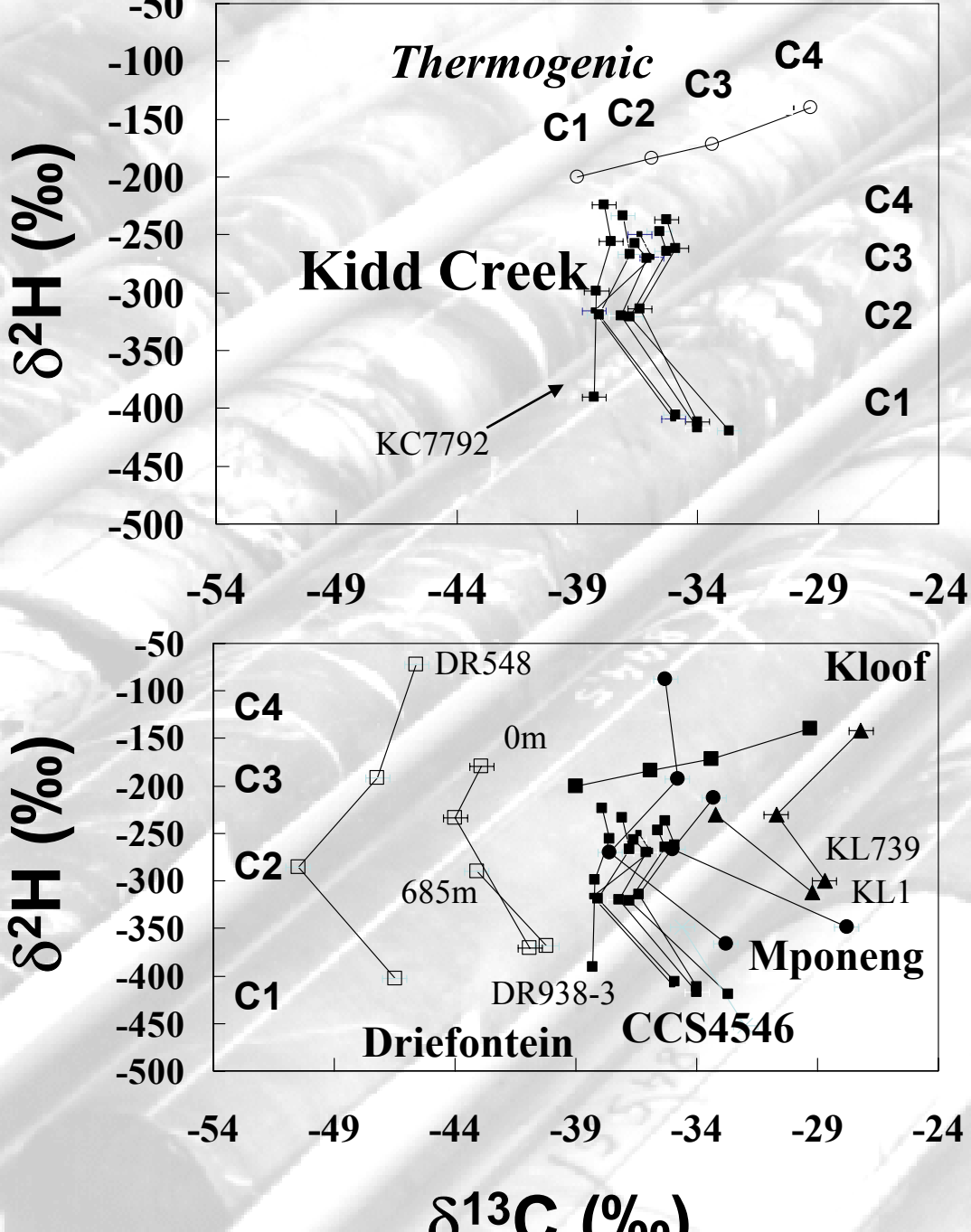
- Obligate anaerobe
- Growth Range: 67-102°C
- Optimum 95°C

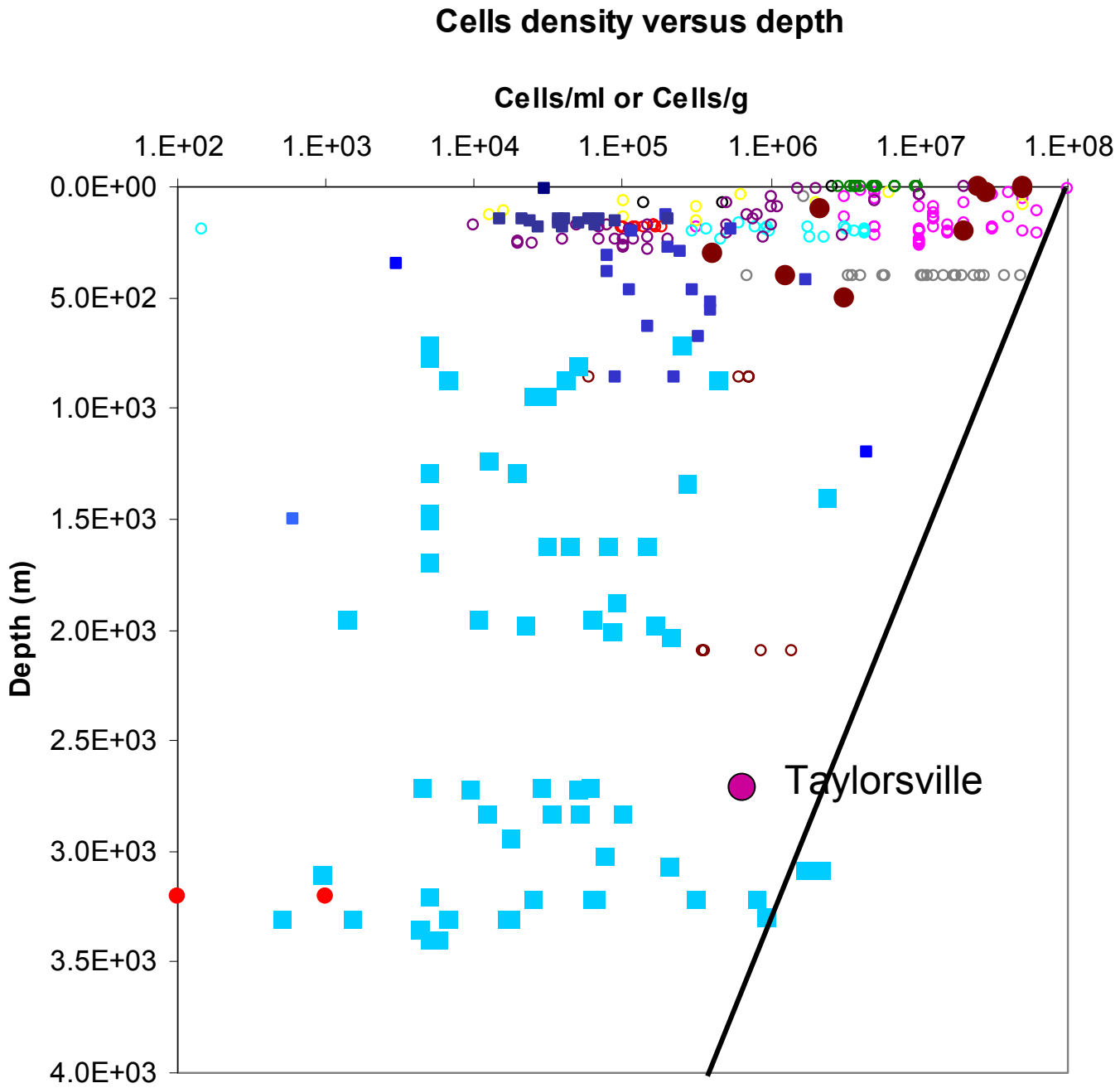
BLACK SMOKER

Radiolytic production of H_2, SO_4^{2-} and $Fe(OH)_3$ supporting abiogenesis and microbial ecosystems?






Thermogenic
C4
C3
C2
C1
Kidd Creek
KC7792
C4
C3
C2
C1
δ2H (‰)
-50
-100
-150
-200
-250
-300
-350
-400
-450
-500
-54
-49
-44
-39
-34
-29
-24
DR548
Kloof
0m
685m
KL739
KL1
Mponeng
DR938-3
CCS4546
Driefontein
δ13C (‰)


Cells density versus depth
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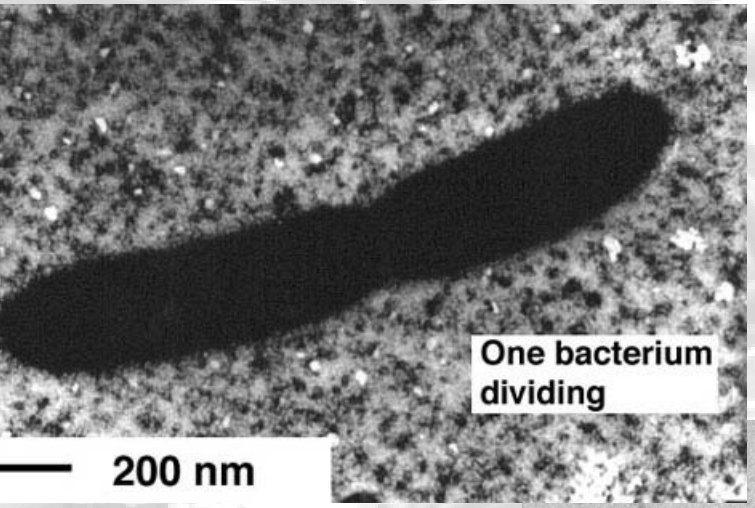
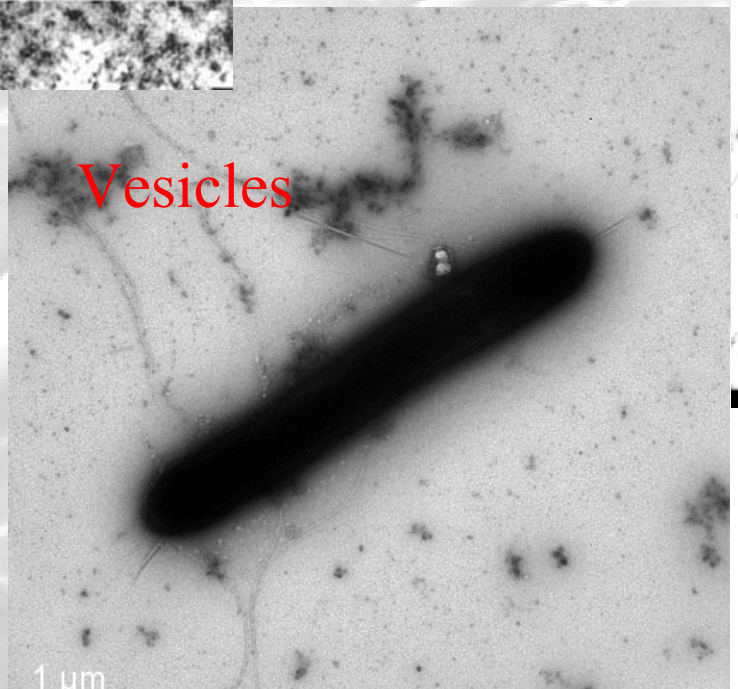
1.E+07
1.E+08
0.0E+00
5.0E+02
1.0E+03
1.5E+03
2.0E+03
2.5E+03
3.0E+03
3.5E+03
4.0E+03
Depth (m)
Taylorsville

- Environment stable for past 50 myr. with last major uplift and microbial incursion at ~90 Ma.
- Biodiversity as defined by 16S rDNA diminishes with depth with some fractures dominated by one species of microorganism.
- Methanogens present at < 2 kmbls.
- Sulfate reducing bacteria dominate at > 2 kmbls.

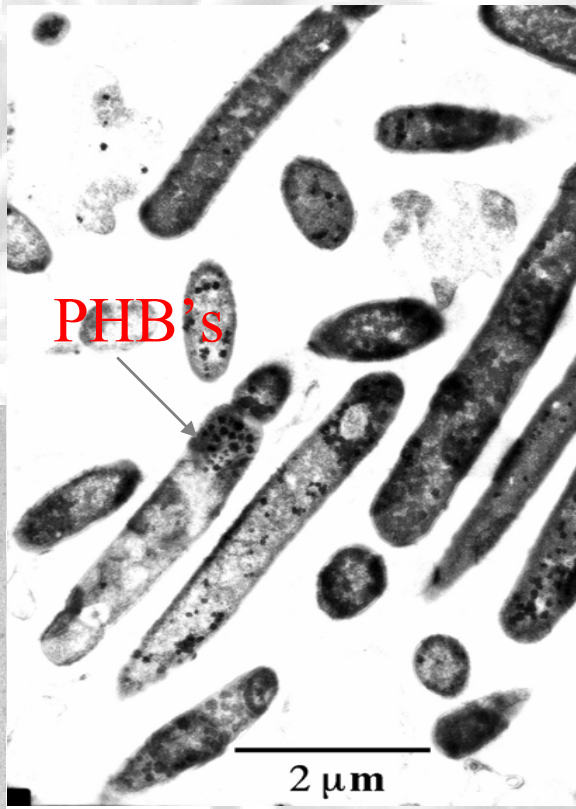
Economically Beneficial S. African Au Mine Bacterial Isolates



Thermus scotoductus



Alkaliphilus aruminator

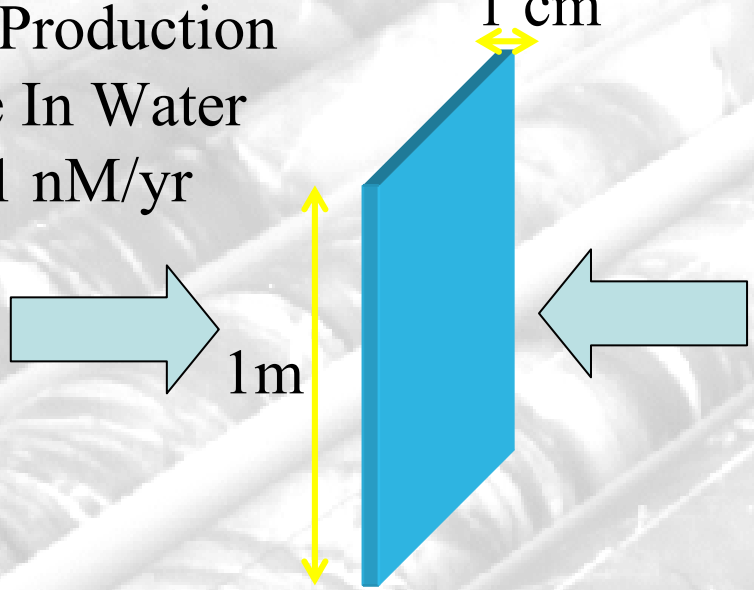


Bacillus thermoaureus

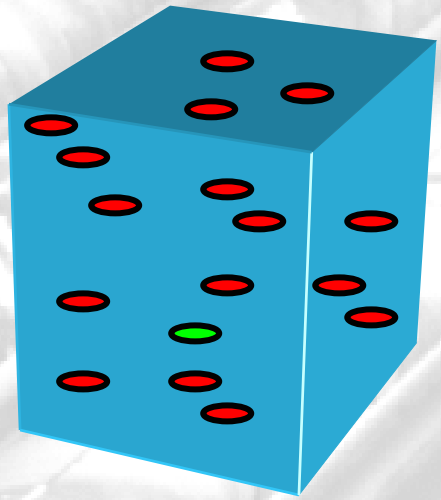
What have we learned?

- Radiolysis supplies a radiochemical factory that can support subsurface life over the long term.
- Abundant, non-photosynthetically derived organic carbon sources are present.
- Can the substrate flux sustain the observed subsurface microbial populations?

Bulk Production Rate In Water 0.1-1 nM/yr

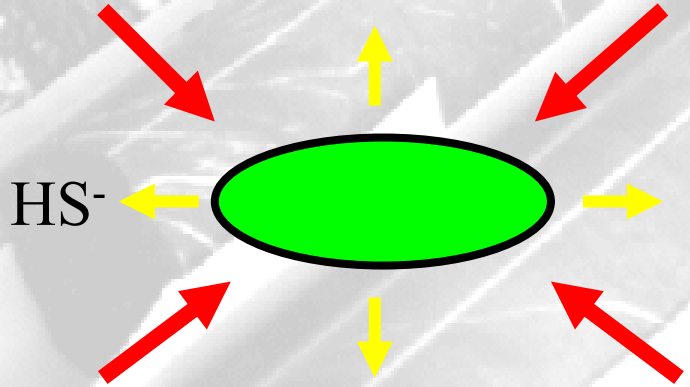


1 Liter

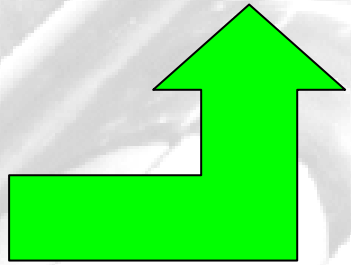


M/yr x cell-yr/moles = #live cells/L

1 x 1 = 1 cell/L vs. 10^{6-9} observed?



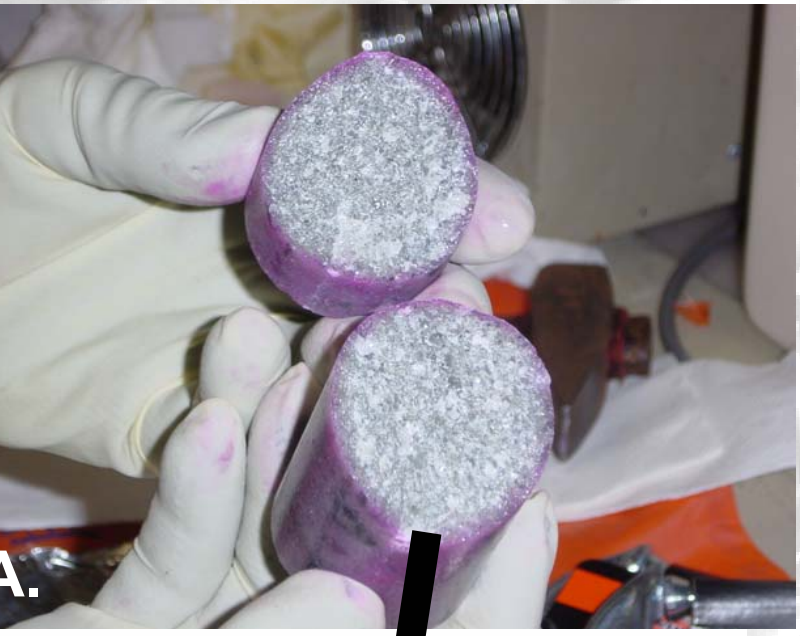
$4\pi DrC$ = 1 nmole cell^{-1} yr^{-1}



$4\pi DrC\Delta G$ = ATP cell^{-1} s^{-1}

Microbial Balance of Power

- Free energy flux = maximum potential power ~ 10^{-13} -10^{-15} kJ cell^{-1} s^{-1}
- Assuming 60 kJ required for ATP synthesis this is equivalent to 10^{-14} -10^{-16} moles of ATP cell^{-1} s^{-1}
- Geochemical estimate of rate ~ 10^{-21} -10^{-23} moles of ATP cell^{-1} s^{-1}
- Maintenance power is ~ 10^{-19} to 10^{-21} moles of ATP cell^{-1} s^{-1} for mesophilic SRB's and methanogens in culture



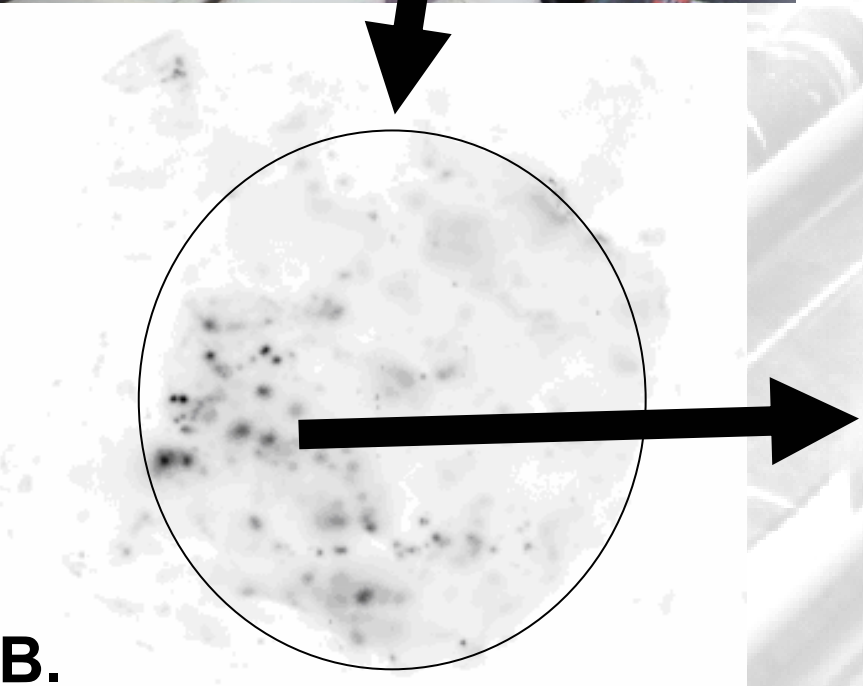
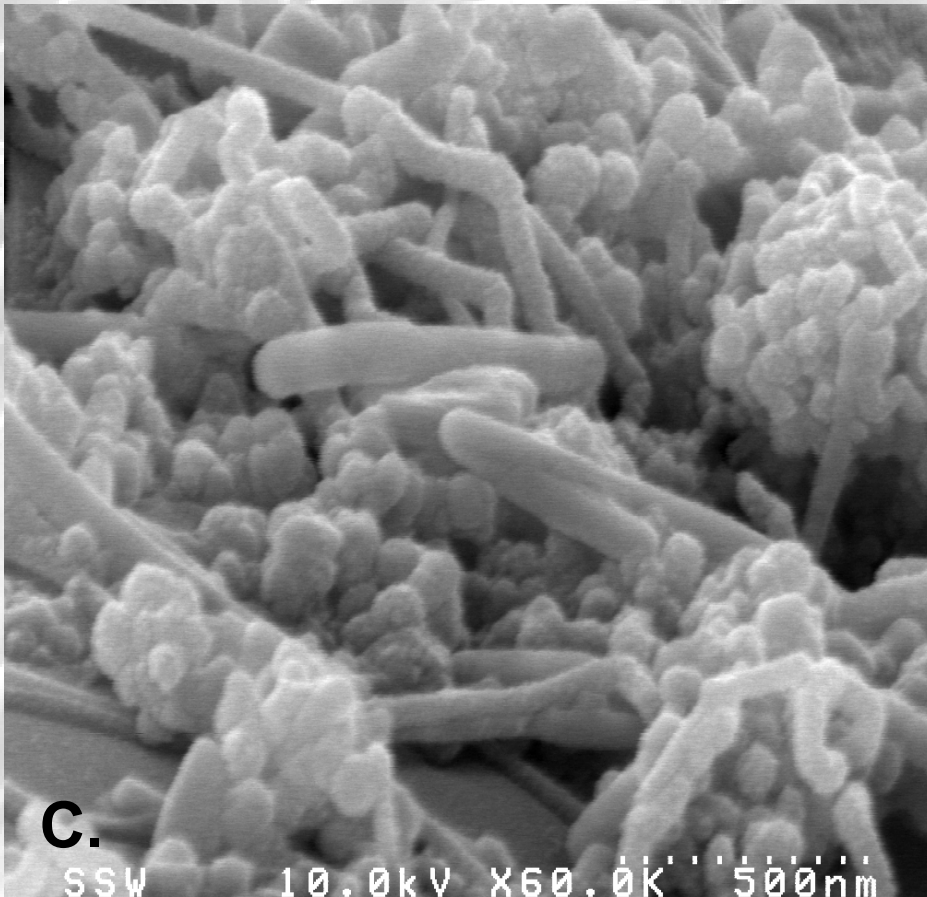
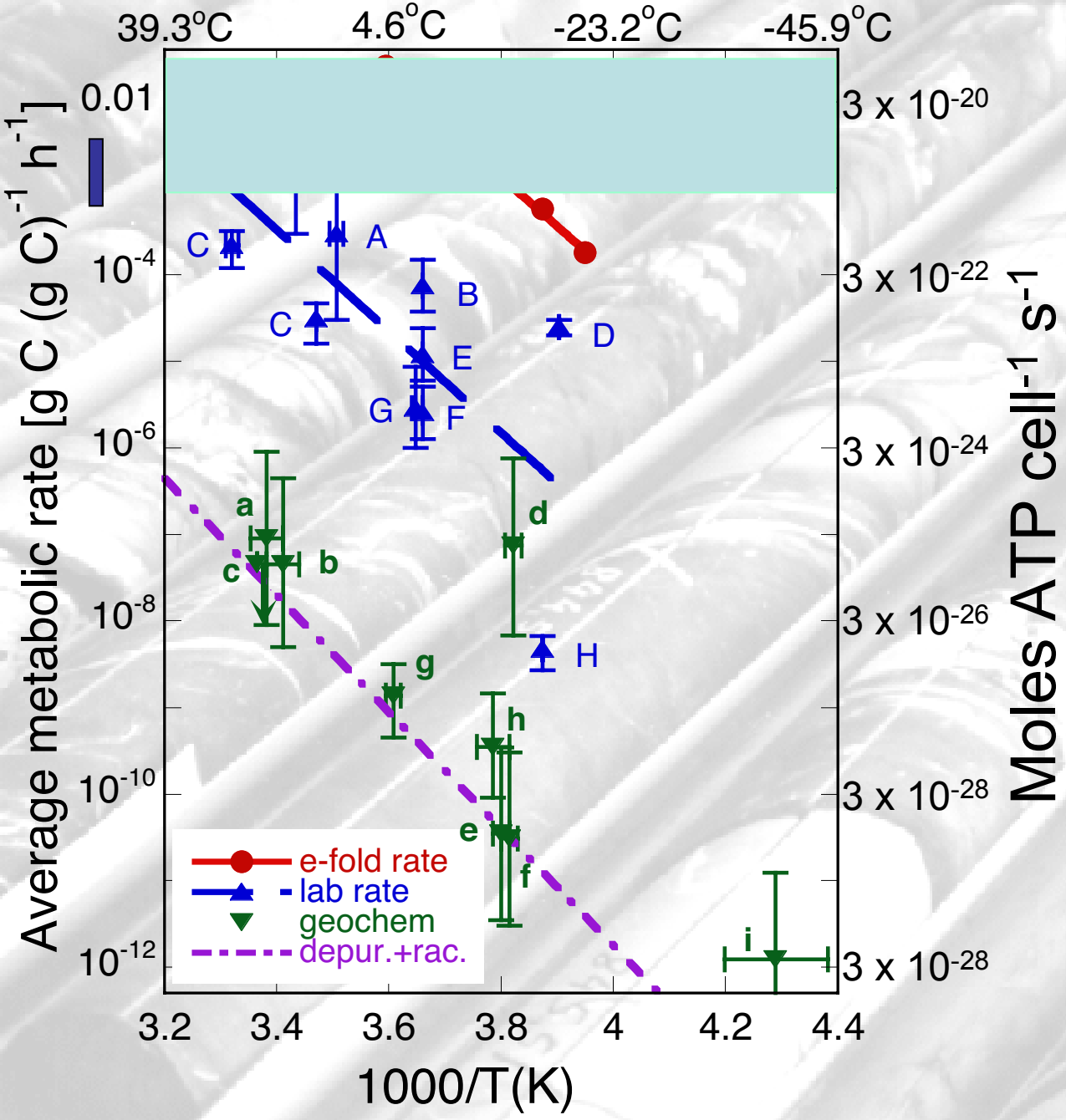
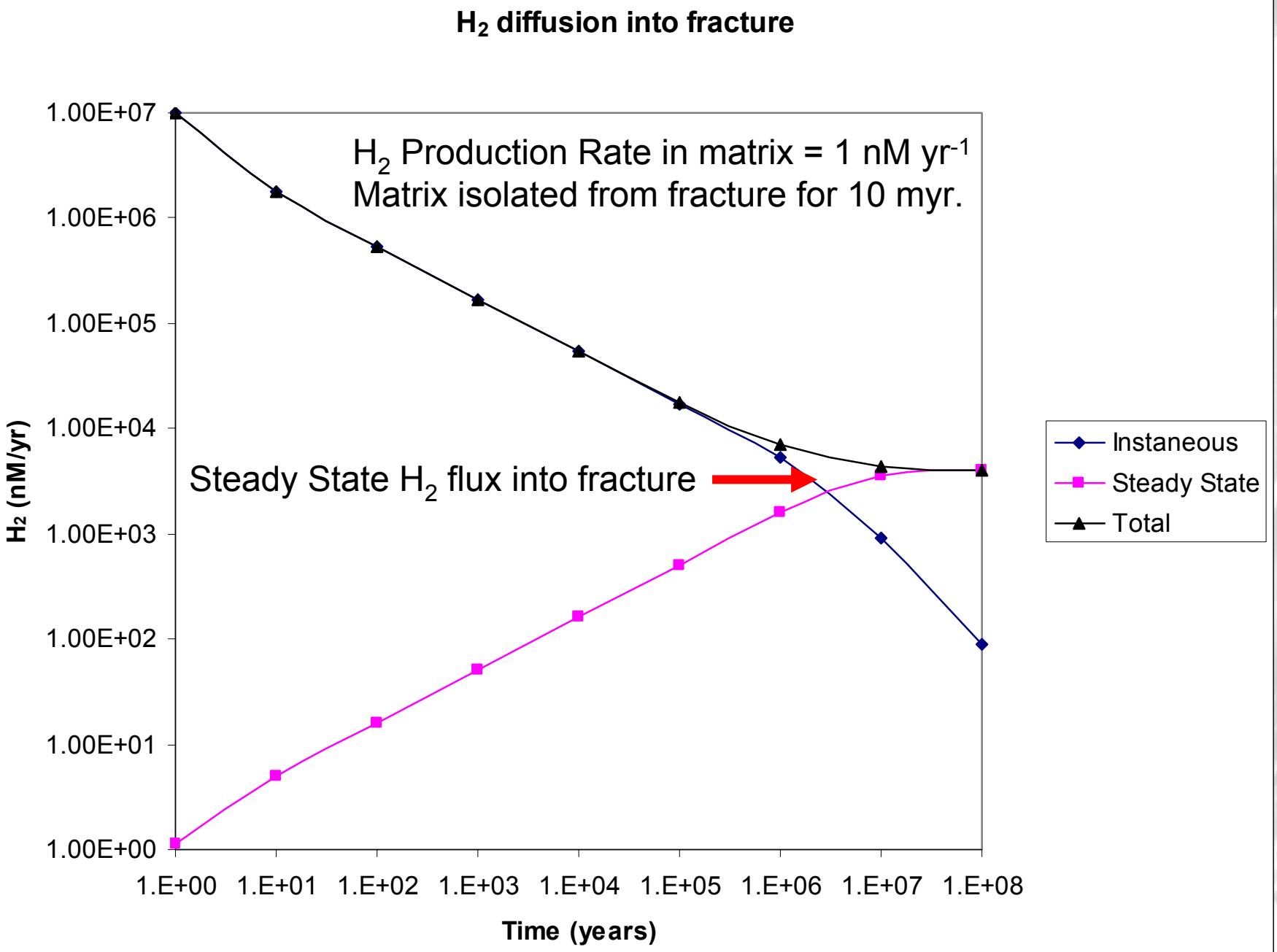


Fig. Xx. A. Witwatersrand quartzite core from 1.95 kilometers beneath land surface. Pink is Rhodamine tracer. B. ^{35}S auto-radiographic image of core. C. Sulfate reducing bacteria with AgS xtals in pore. Scale bar is 500 nm. Courtesy of Gordon Southam, Univ. of Western Ontario and Mark Davidson, Princeton University.




39.3°C
4.6°C
-23.2°C
-45.9°C
Average metabolic rate [g C (g C)-1 h-1]
0.01
10-4
10-6
10-8
10-10
10-12
3 x 10-20
3 x 10-22
3 x 10-24
3 x 10-26
3 x 10-28
3 x 10-28
Moles ATP cell-1 s-1
A
B
C
C
D
E
F
G
H
a
b
c
d
e
f
g
h
i
e-fold rate
lab rate
geochem
depur.+rac.
3.2
3.4
3.6
3.8
4
4.2
4.4
1000/T(K)


Death-O-Meter
Geochemical Est.
Free Energy Flux
Chemically reactive cellular remains
Cannot be cultured
Macromolecules
Starvation
Activity
Can be resuscitated
Diagenesis
LIFE
DEATH
Growth
Procreation
Minerals
ORGANICS
MINERALIZATION
Can be cultured
Continuum Meter

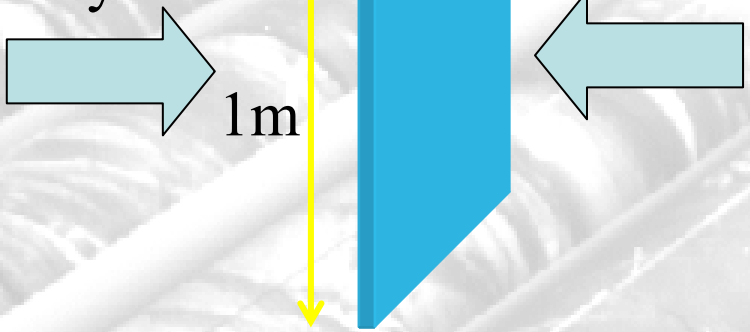

H2 diffusion into fracture
H2 Production Rate in matrix = 1 nM yr-1
Matrix isolated from fracture for 10 myr.
Steady State H2 flux into fracture
1.00E+07
1.00E+06
1.00E+05
1.00E+04
1.00E+03
1.00E+02
1.00E+01
1.00E+00
H2 (nM/yr)
1.E+00
1.E+01
1.E+02
1.E+03
1.E+04
1.E+05
1.E+06
1.E+07
1.E+08
Time (years)
Instaneous
Steady State
Total

Diffusive Flux
Into Fracture

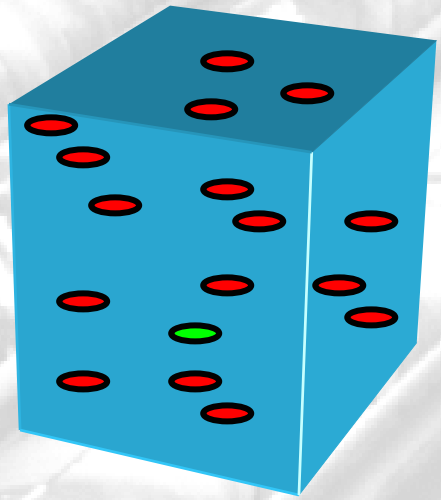
1 cm

10^4 nM/yr

1m



1 Liter



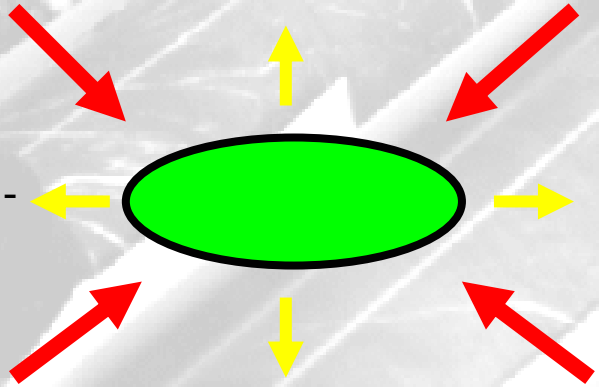
nM/yr x cell-yr/nmoles = #live cells/L

10^4 x 1 = 10^4 cells/L vs. 10^{6-9} observe

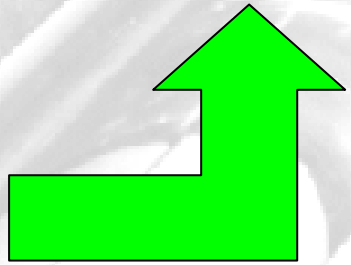
H_2

SO_4^{2-}

HS^-



$4\pi DrC$ = 1 nmole cell^{-1} yr^{-1}

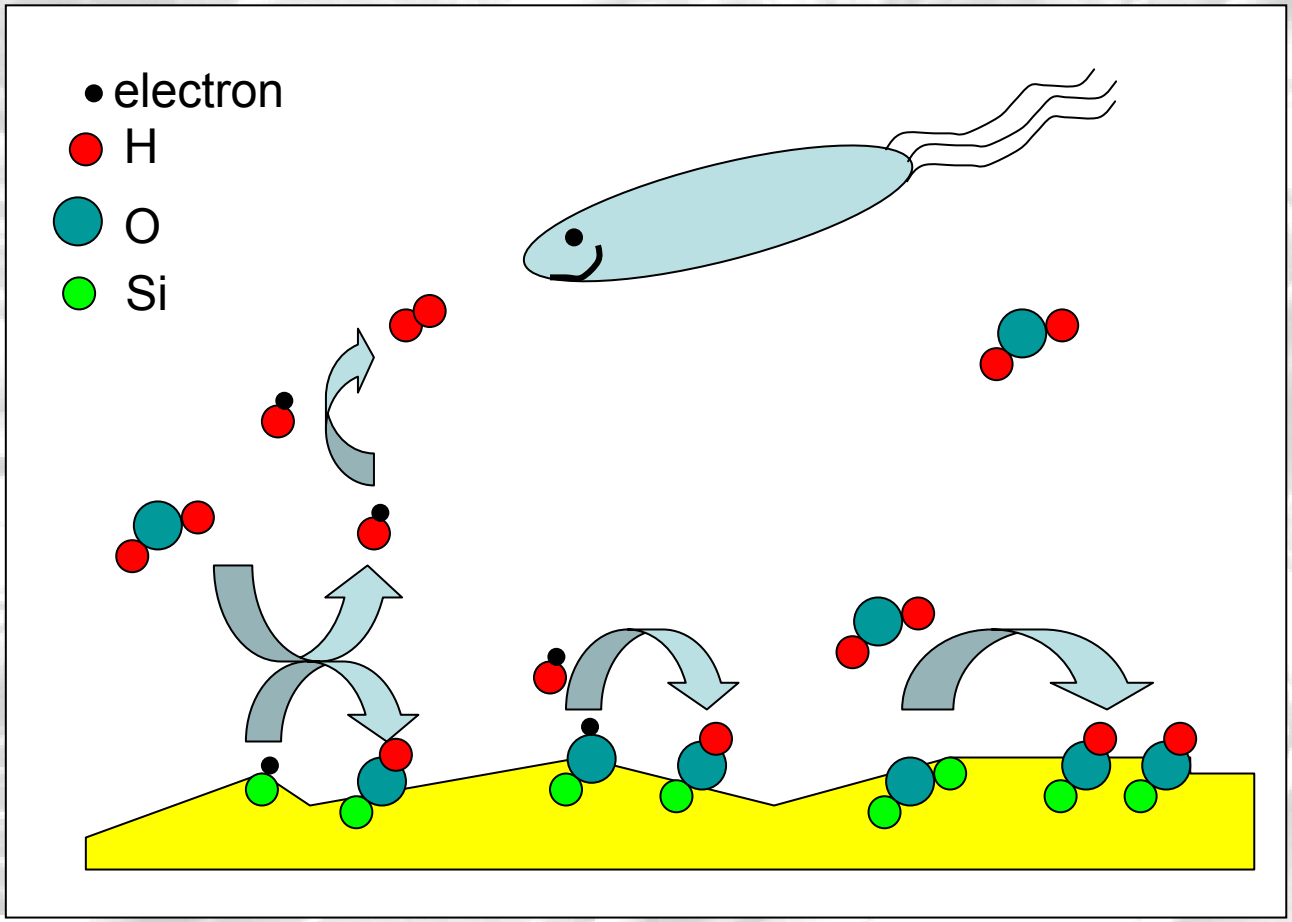


$4\pi DrC\Delta G$ = ATP cell^{-1} s^{-1}

What's going on?

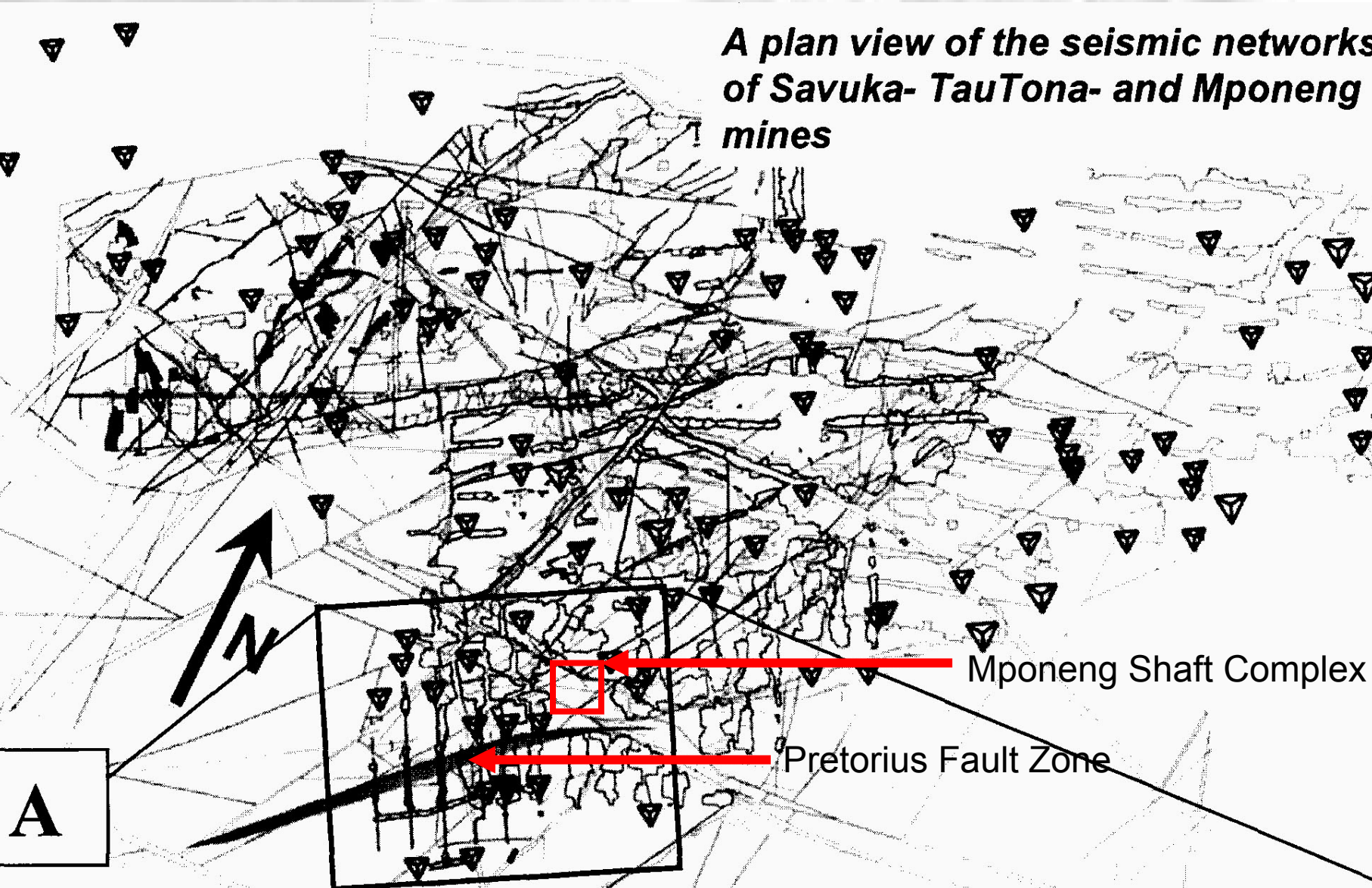
- Are most of the cells that we see essentially dead (moriobound)?
- Is the origin of the substrate more complex, i.e. are the microorganisms switching metabolisms when the ΔG approaches 0?
- Is mining induced fracturing enhancing substrate flux rates-i.e. 10^7 nM yr-1, that cannot be sustained in the long haul?

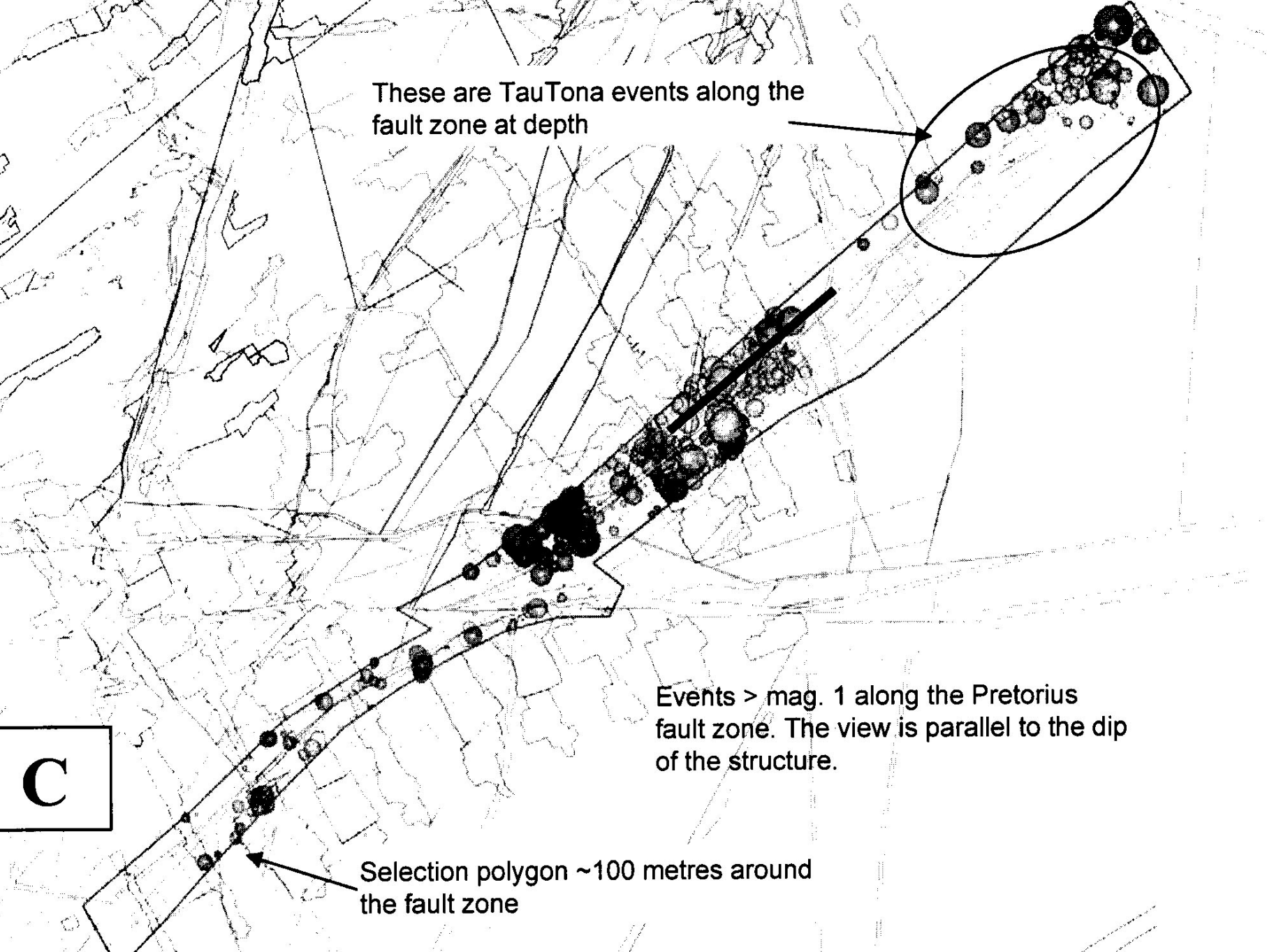
Can fracturing enhance redox flux by other mechanisms?

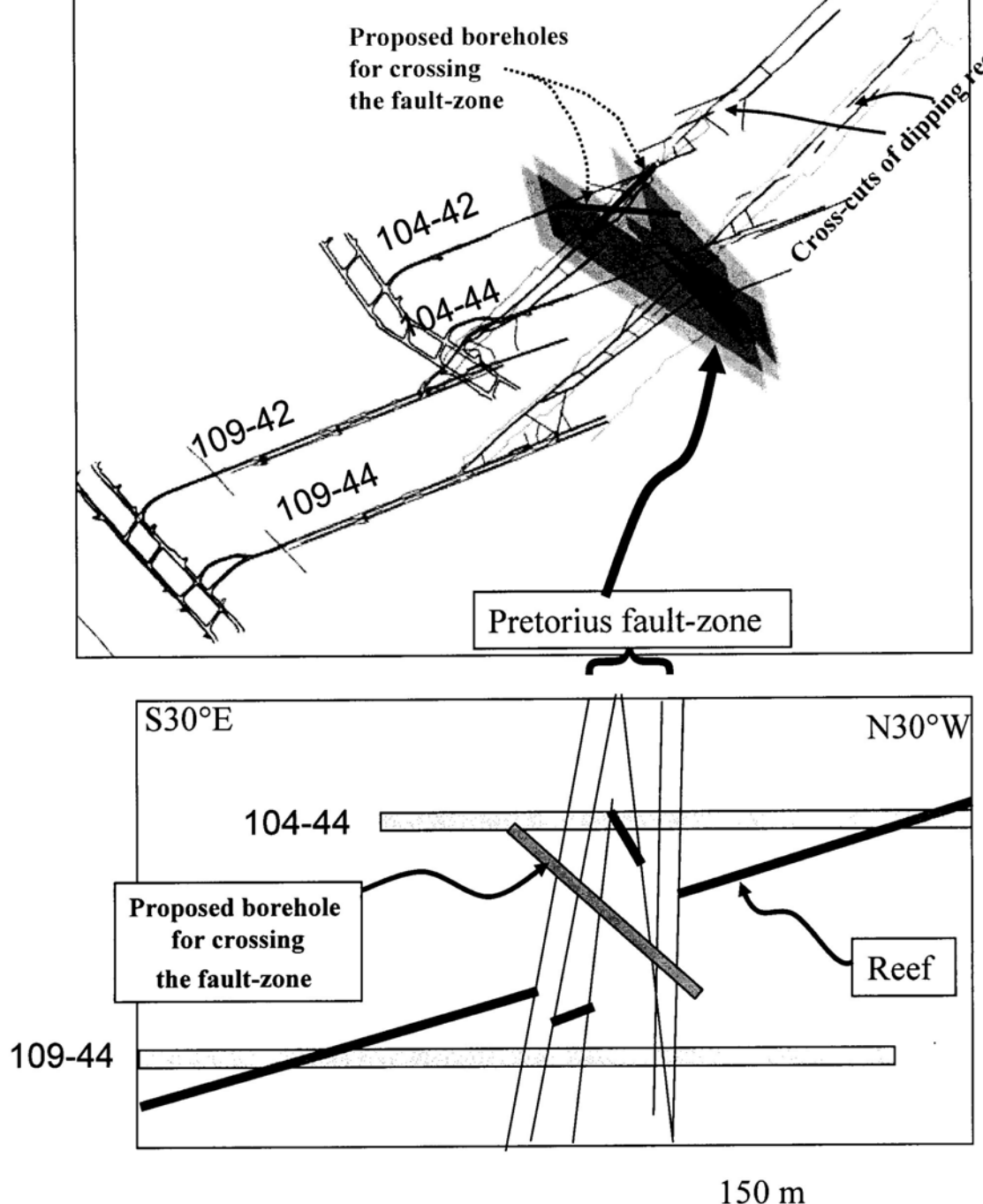


H_2 Generation from H_2O reacting with fractured SiO_2

Drilling and Monitoring an Active Fault in a South African Mine




These are TauTona events along the fault zone at depth
Events > mag. 1 along the Pretorius fault zone. The view is parallel to the dip of the structure.
C
Selection polygon ~100 metres around the fault zone


Proposed boreholes
for crossing
the fault-zone
Cross-cuts of dipping reef
104-42
104-44
109-42
109-44
Pretorius fault-zone
S30°E
N30°W
104-44
Proposed borehole
for crossing
the fault-zone
Reef
109-44
150 m

Near-field observation of Earthquake induced gas release

J. Lippmann, S. Niedermann, M. Zimmer, J. Erzinger, GFZ Potsdam, Germany

GFZ POTSDAM

Core analysis

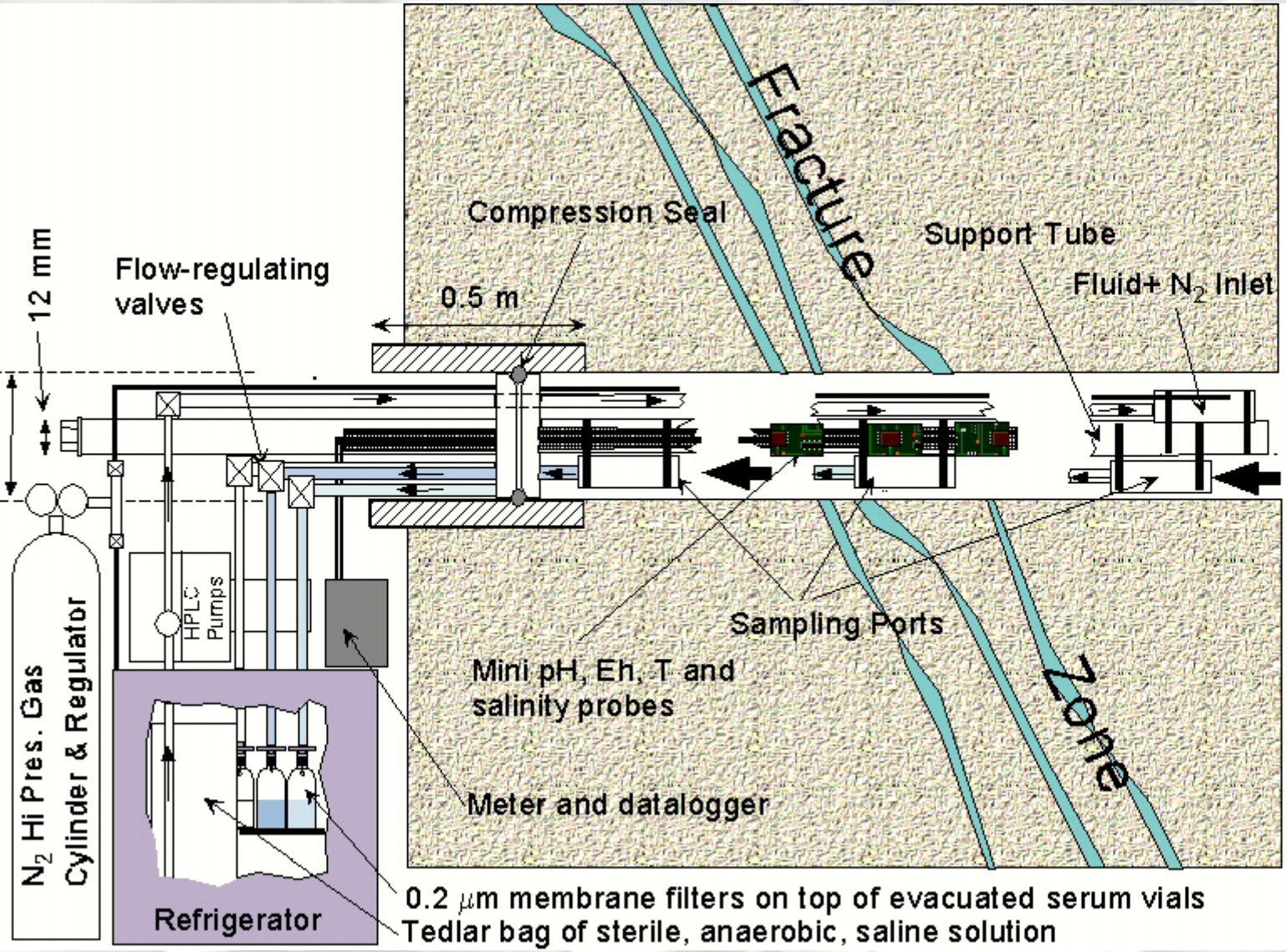
- On-site sampling of ~10 freshly drilled core segments from across the fault
- sealing cores in evacuated containers for lab analysis
- Stepwise heating of core material and mass spec analysis of released noble gas isotopes (room temp – 1800°C, routine procedure)

  Thermal characterization of outgassing processes (field+lab)

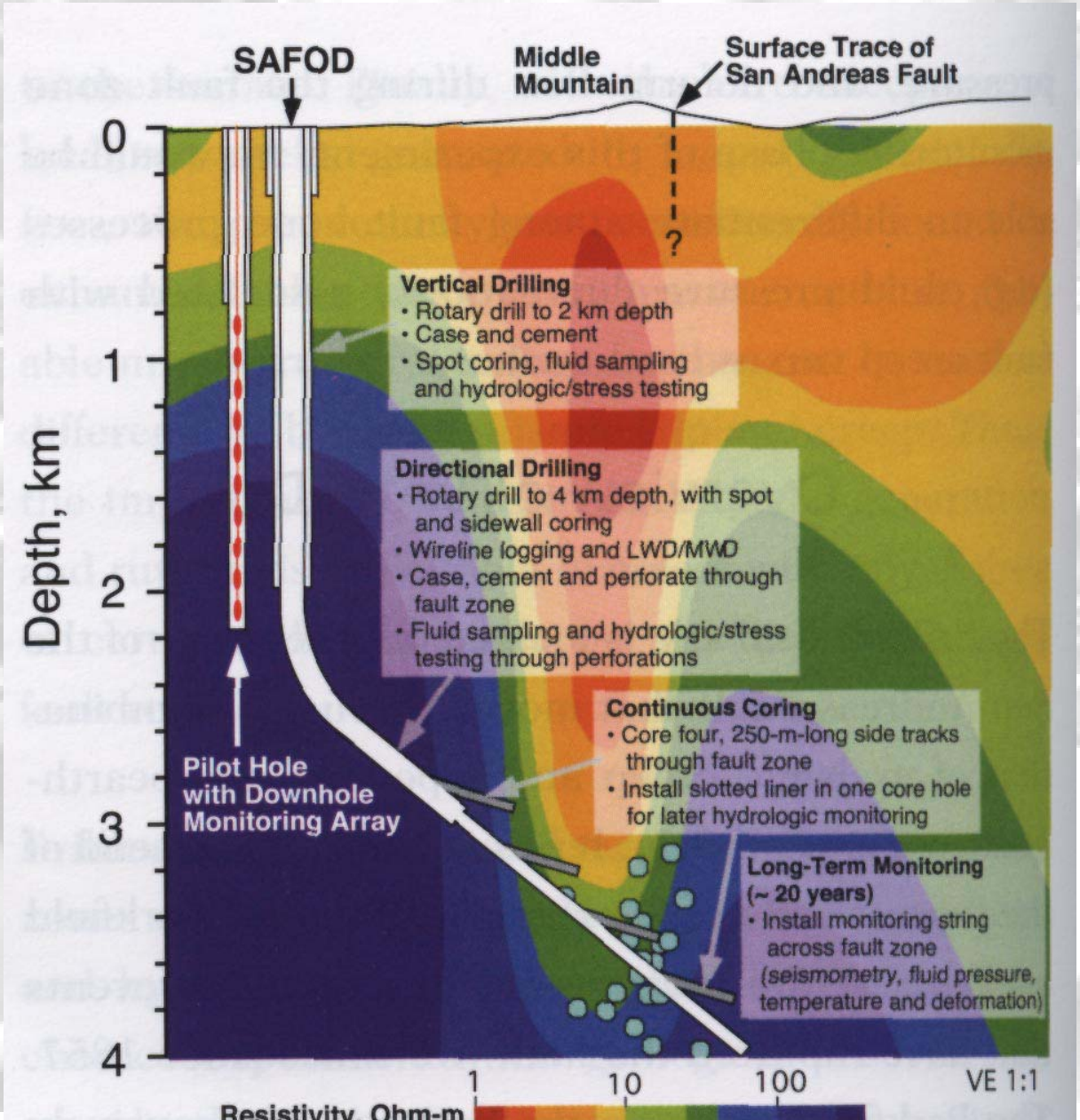
• Online gas monitoring

- Continuous analysis of borehole gas by a quadrupole mass spectrometer (He, Ne, Ar, CO_2, CH_4, N_2, O_2 , H_2)
- Gas is sucked through multi tube system from ~5 locations inside borehole
- Threshold signal (He, CH_4) triggers special gas sampling device (glass vials) for off-line analysis in lab

  Earthquake induced outgassing process (field)


Fracture
Compression Seal
Support Tube
Fluid+ N_2 Inlet
12 mm
Flow-regulating valves
0.5 m
HPLC Pumps
Sampling Ports
Mini pH, Eh, T and salinity probes
Zone
Meter and datalogger
N_2 Hi Pres. Gas Cylinder & Regulator
Refrigerator
0.2 μm membrane filters on top of evacuated serum vials
Tedlar bag of sterile, anaerobic, saline solution

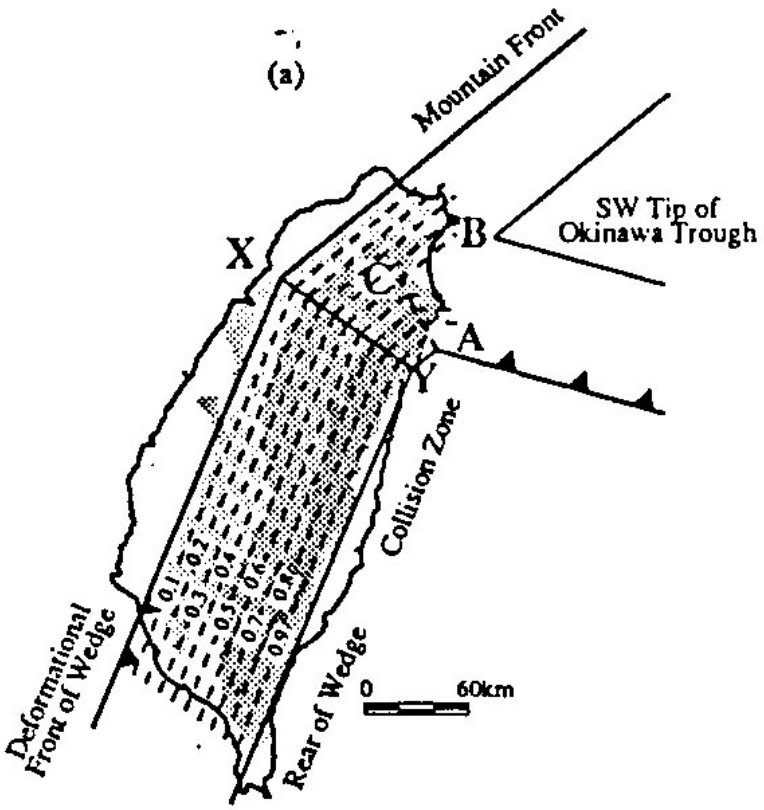
San Andreas Fault Zone Coring and Monitoring

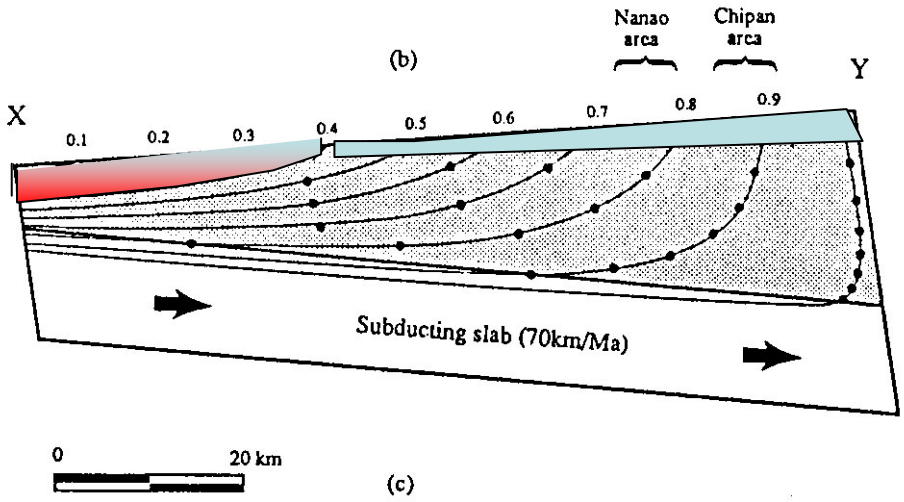


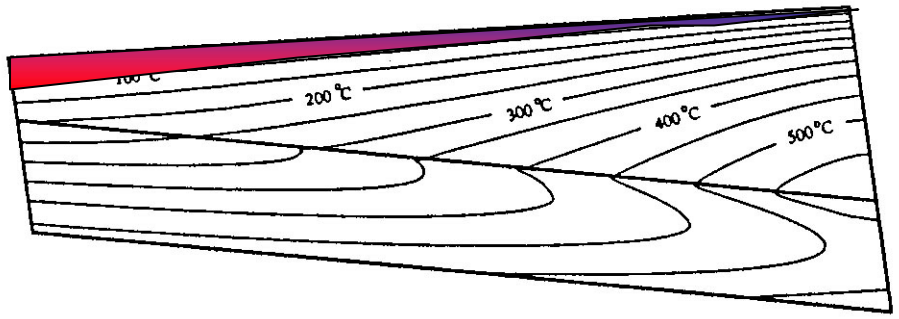
Temperatures of 80° to 200°C.

High conductivity (salinity?) anomaly within fault zone.

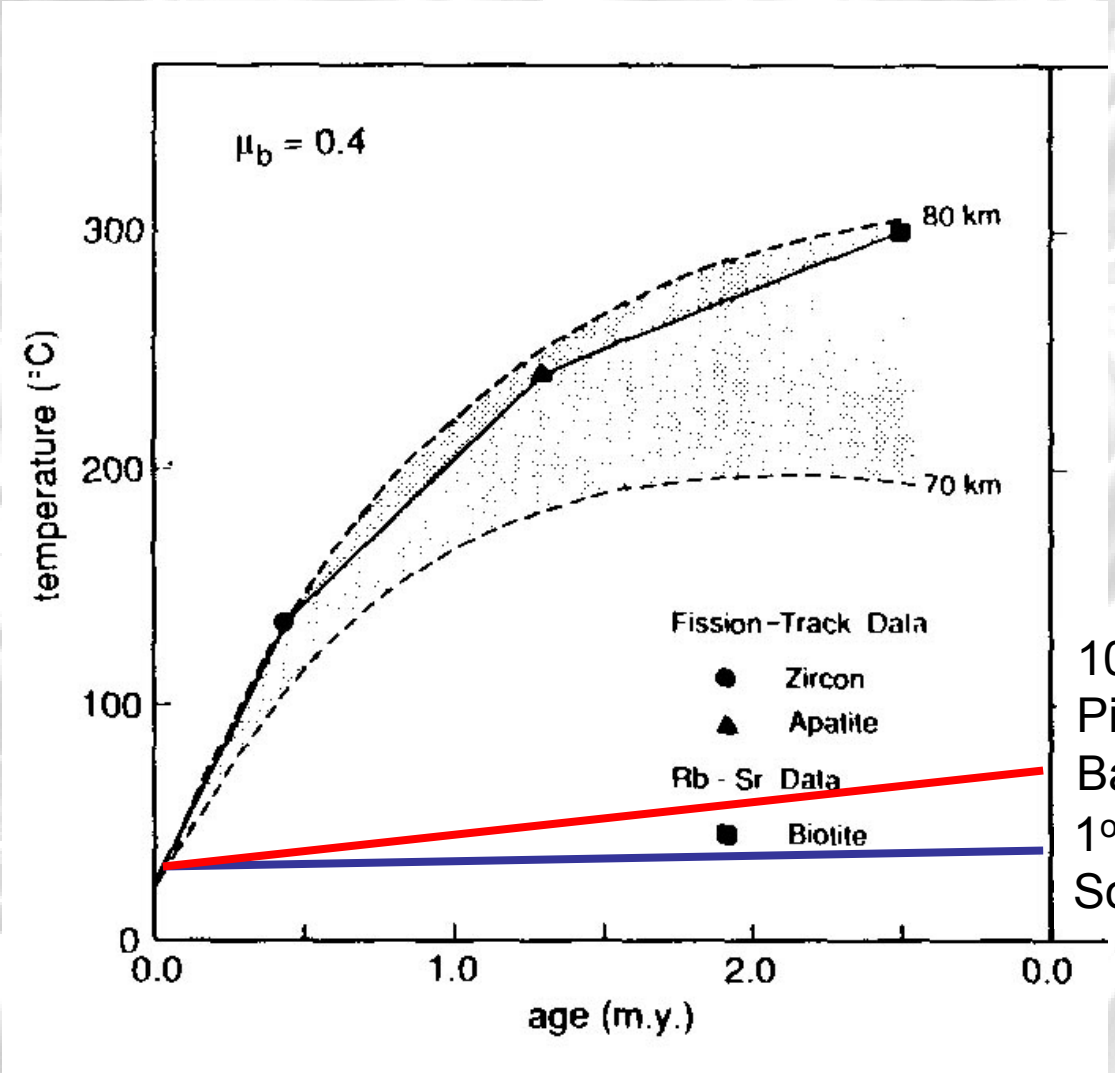
Will the origin of deep subsurface microorganisms vary across Taiwan?







Can microbial colonization keep pace with tectonic uplift?



10°C/Ma
Piceance
Basin

1°C/Ma
South Africa

Two Questions

1. How can deep subsurface microbial communities survive tens or hundreds of millions of years separated from the photosphere?
2. Are the deep subsurface microbial and nutrient fluxes greater in tectonically active environments than in quiescent crustal or marine sedimentary environments?