Hydrogeology of the Soudan Mine, Minnesota: Applications to Terrestrial - and - Extra-terrestrial Research

6 AMay2010 MGWA Spring Meeting

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Ryan Lesniewski, UG, UM

Penny Boston, NM Tech

Phil Bennett, UT Austin

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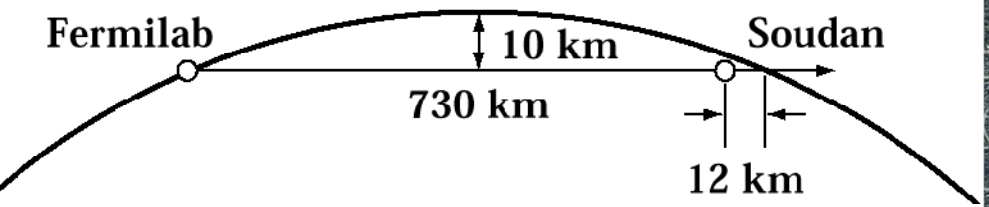
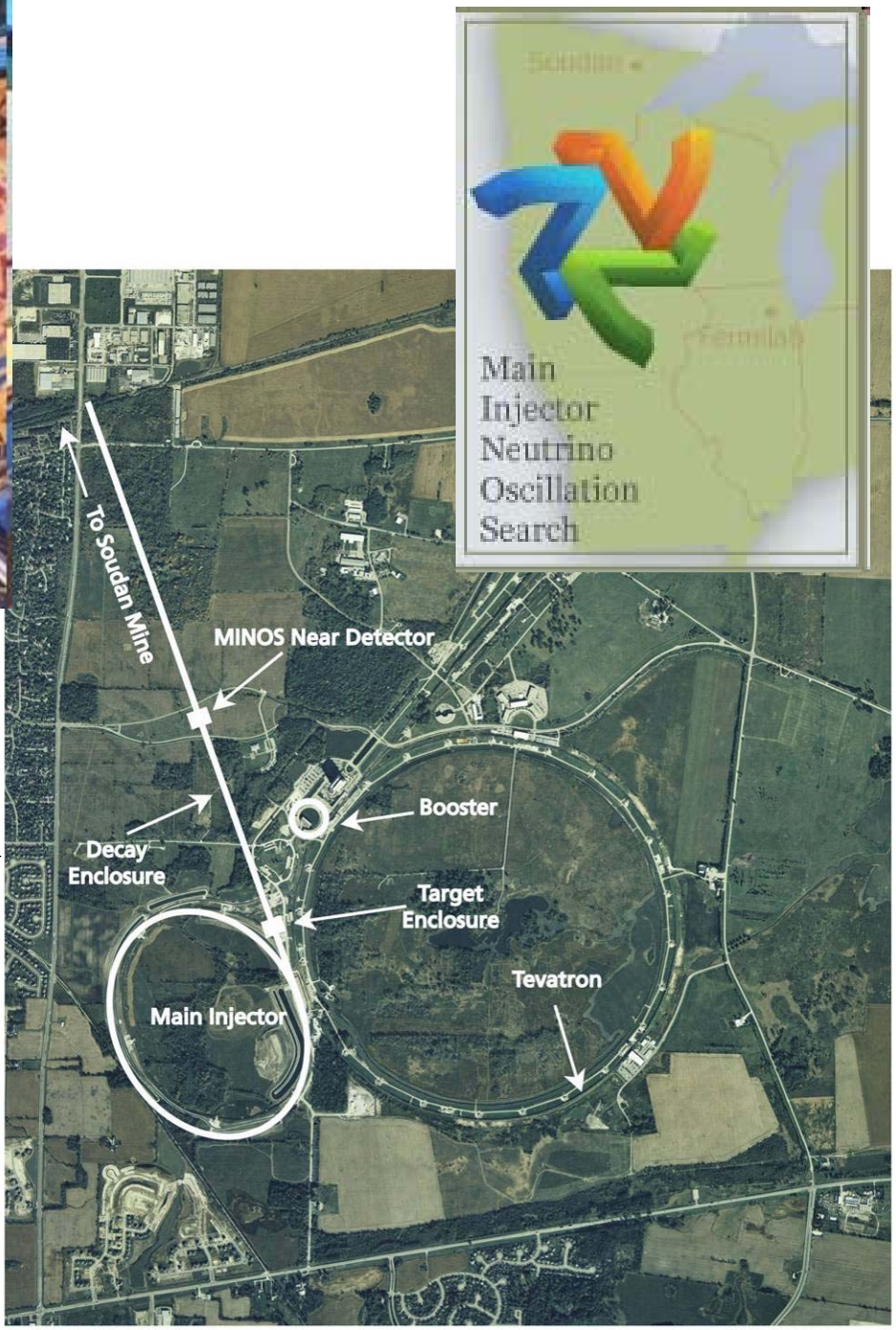
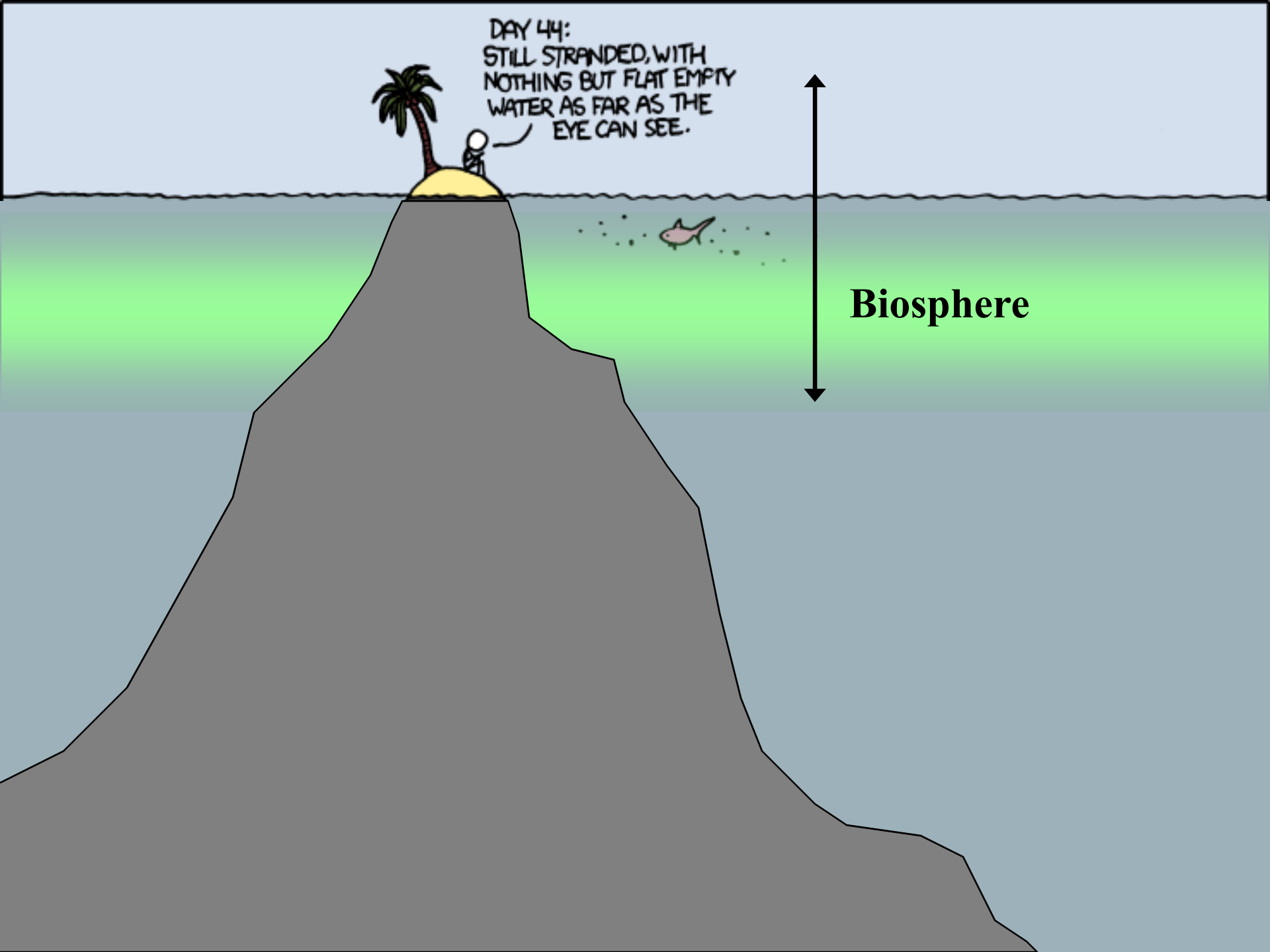
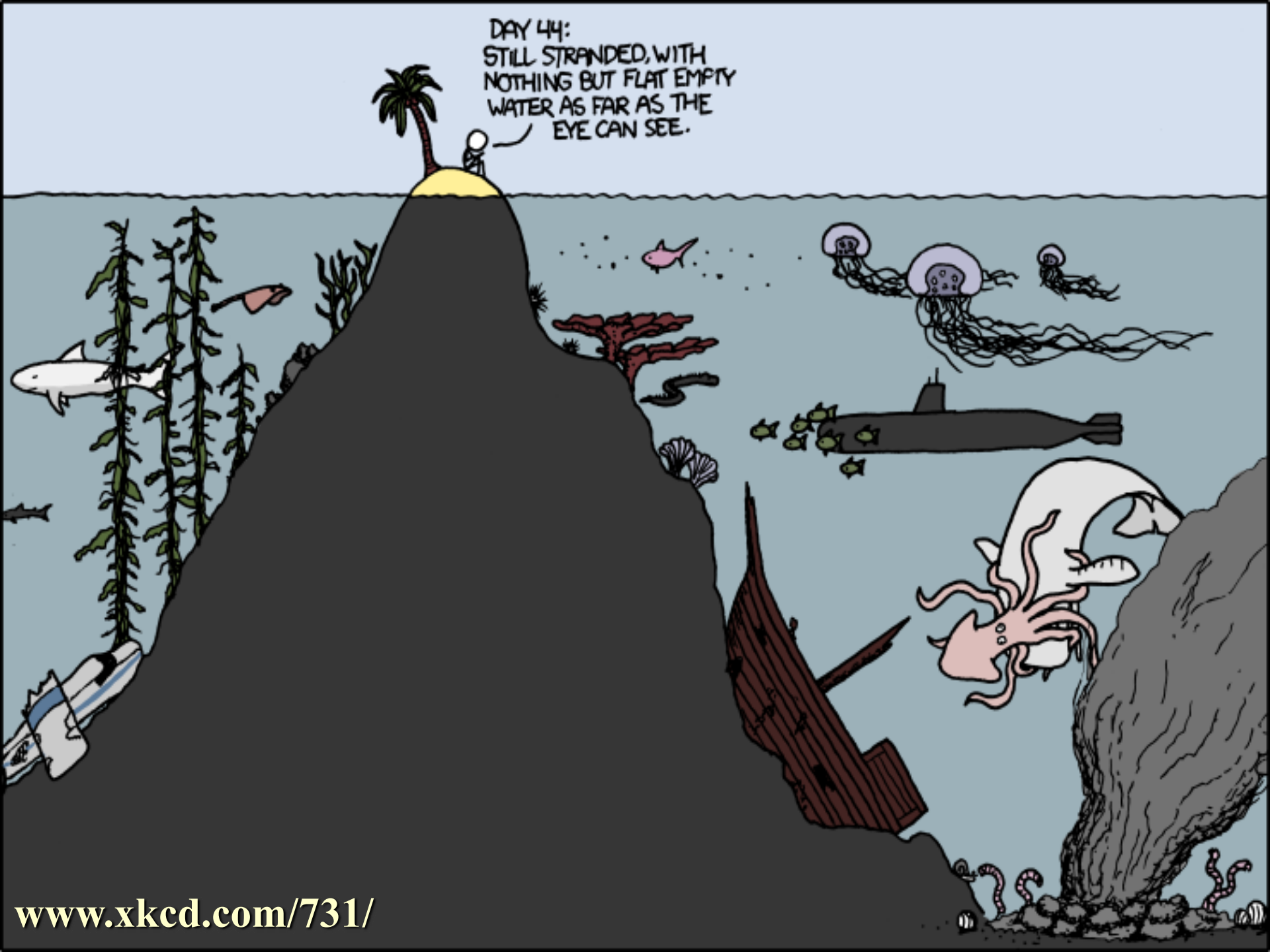
Brandy Toner, SWC, UM

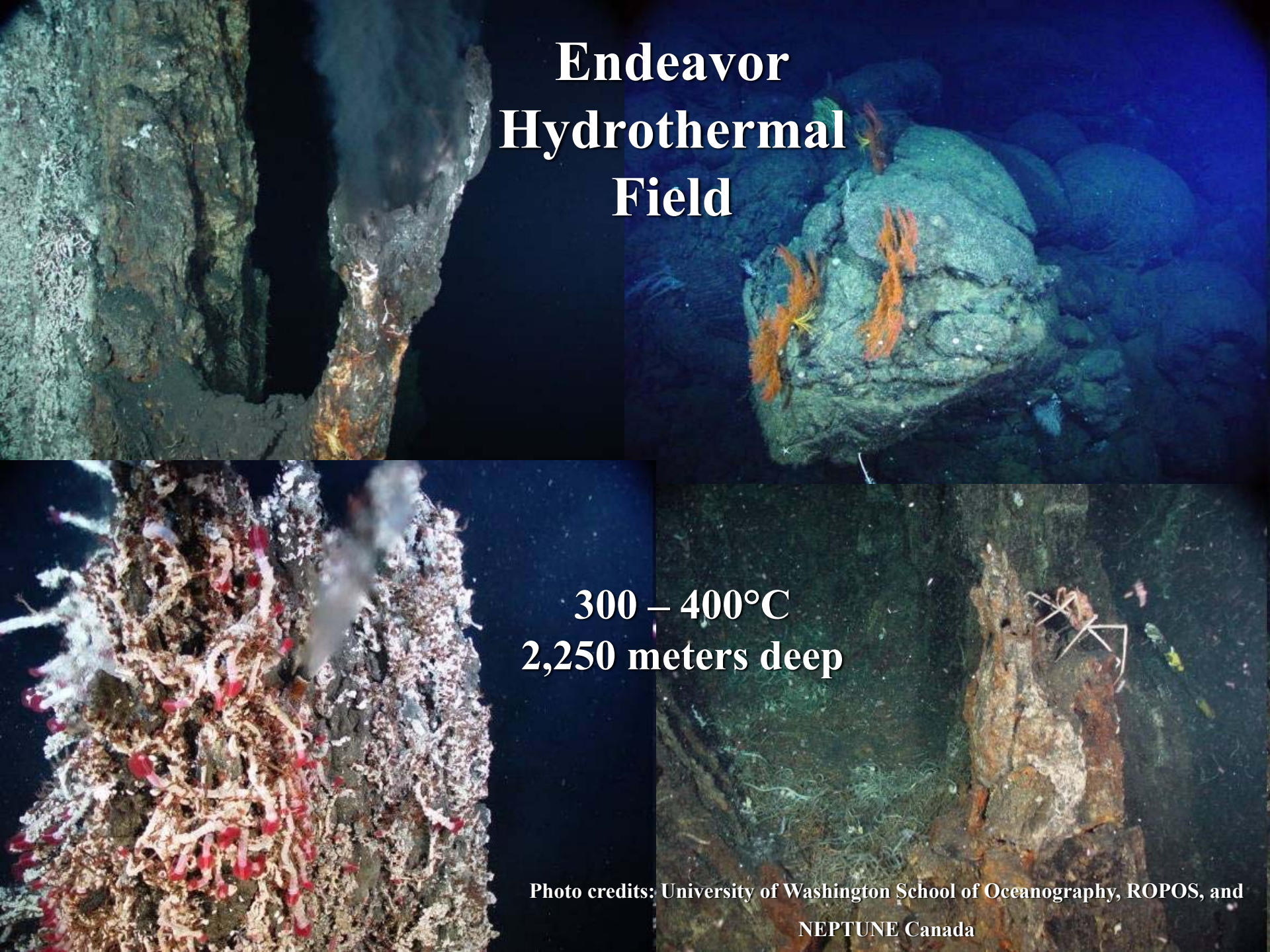


U of M High Energy Physics




DAY 44:
STILL STRANDED, WITH NOTHING BUT FLAT EMPTY WATER AS FAR AS THE EYE CAN SEE.
Biosphere


DAY 44:
STILL STRANDED, WITH NOTHING BUT FLAT EMPTY WATER AS FAR AS THE EYE CAN SEE.
www.xkcd.com/731/



Endeavor Hydrothermal Field

300 – 400°C
2,250 meters deep

Photo credits: University of Washington School of Oceanography, ROPOS, and NEPTUNE Canada

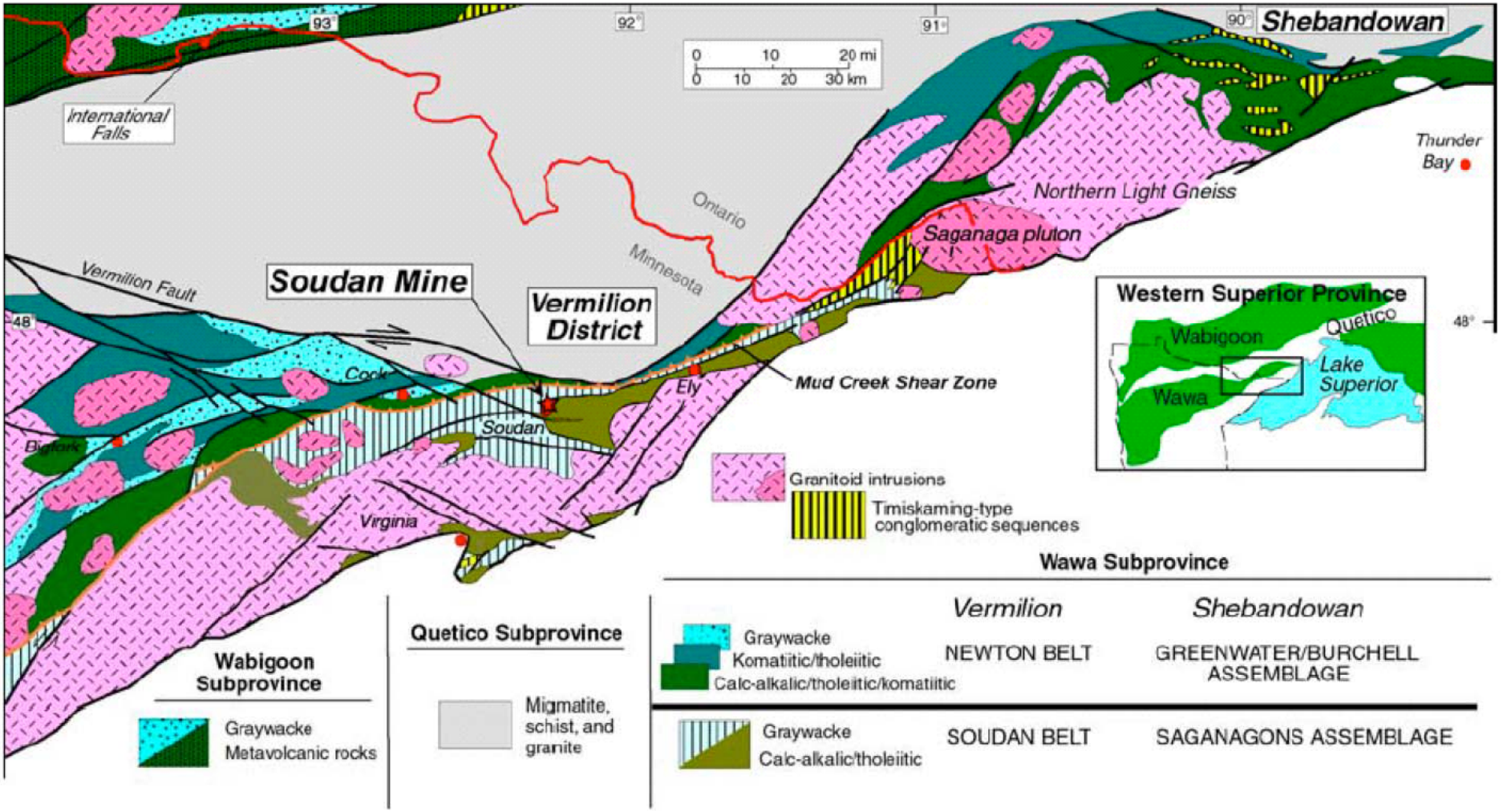


Figure 1. Simplified tectono-stratigraphic map of the Late Archean terranes surrounding the Soudan Mine.

Peterson & Patelke 2003

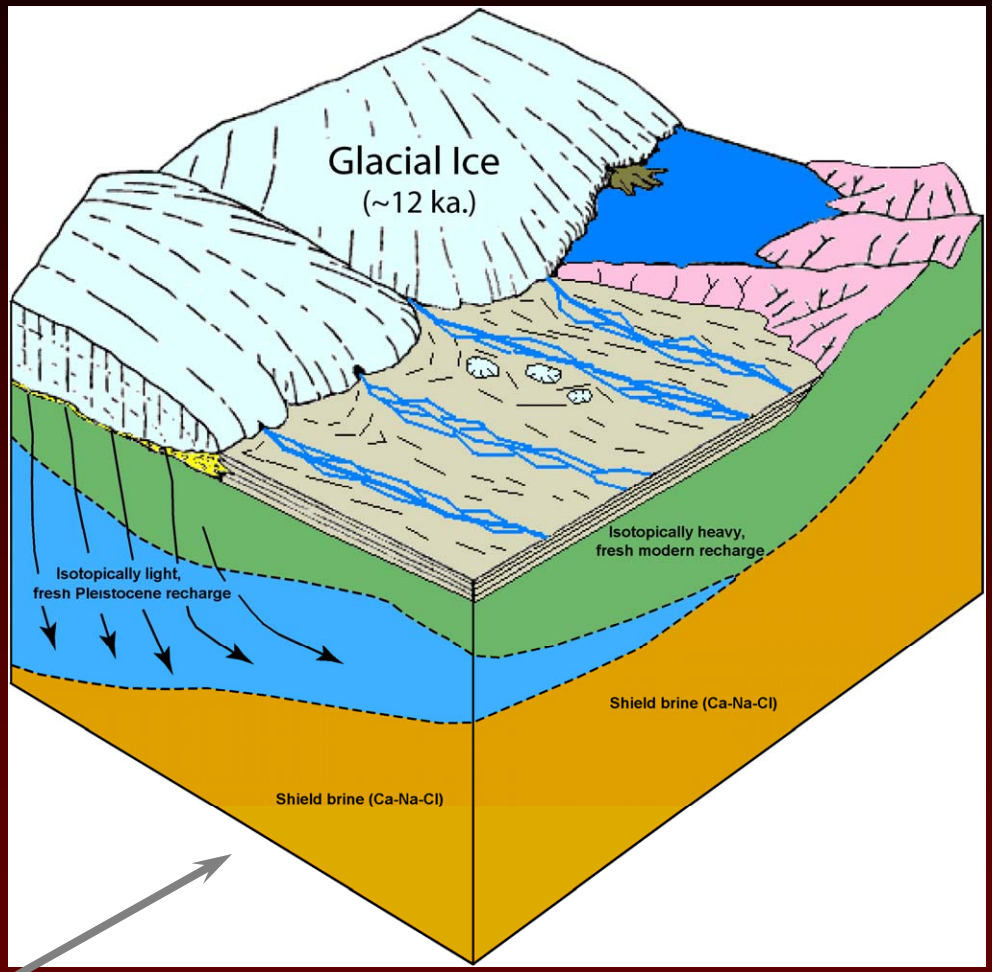
Hydrologic Environment

- Surface waters drain NW into Lake Vermilion
  - Lake Area: 40,557 acres
  - Littoral Area (<15 ft deep): 15,006 acres
  - Maximum Depth: 76 ft
- Shallow water table (locally at surface)
  - Beaver dams, ponds, Lakes
- Thin surficial sediments
- Hard, fractured igneous and metamorphic bedrock

Hypothesized Groundwater Types

Soudan analog along the Vermilion Moraine

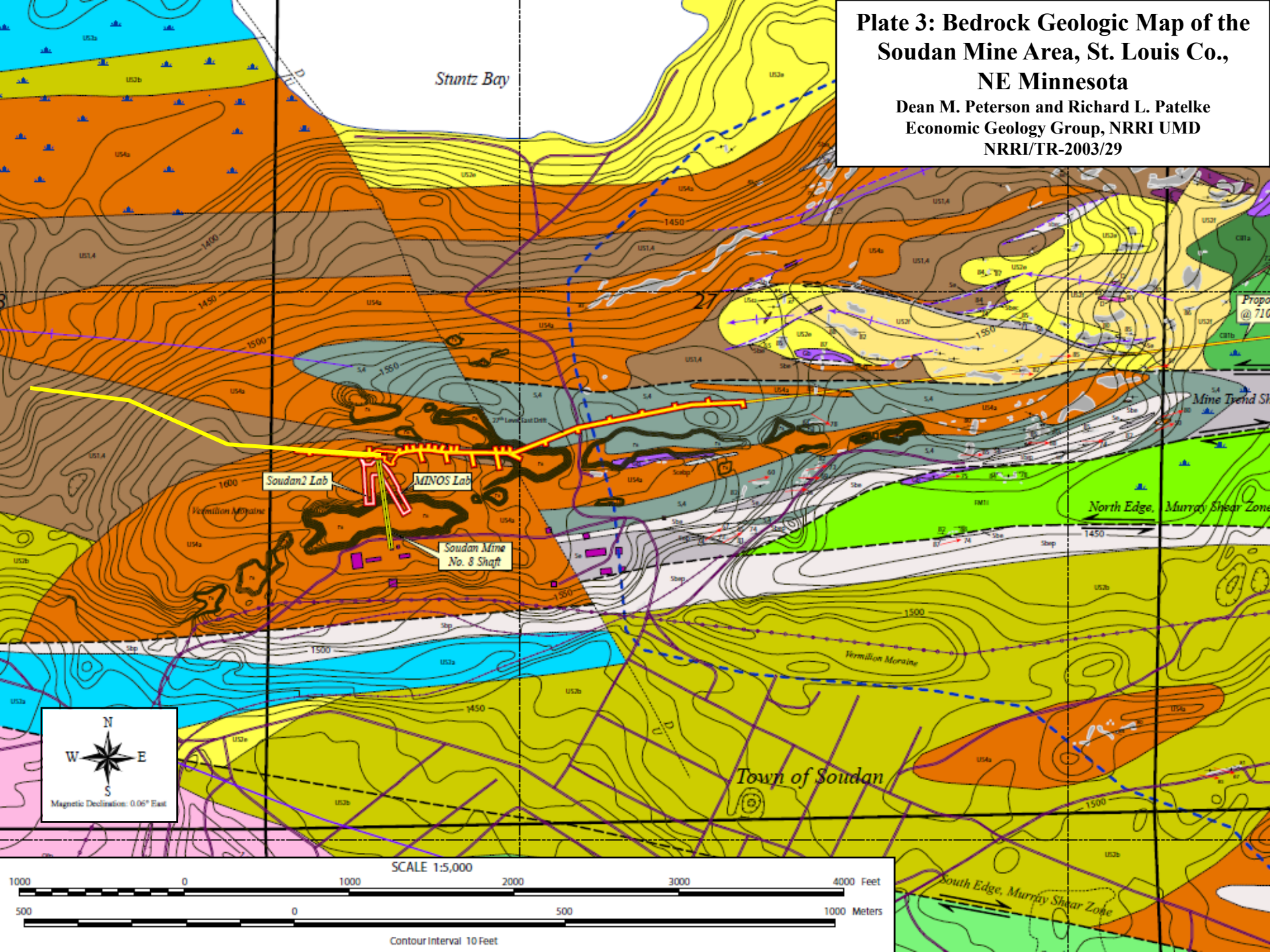
Near ice sheet margins, steep topographic gradients are predicted to induce deep flow of glacial meltwater into underlying substrate.



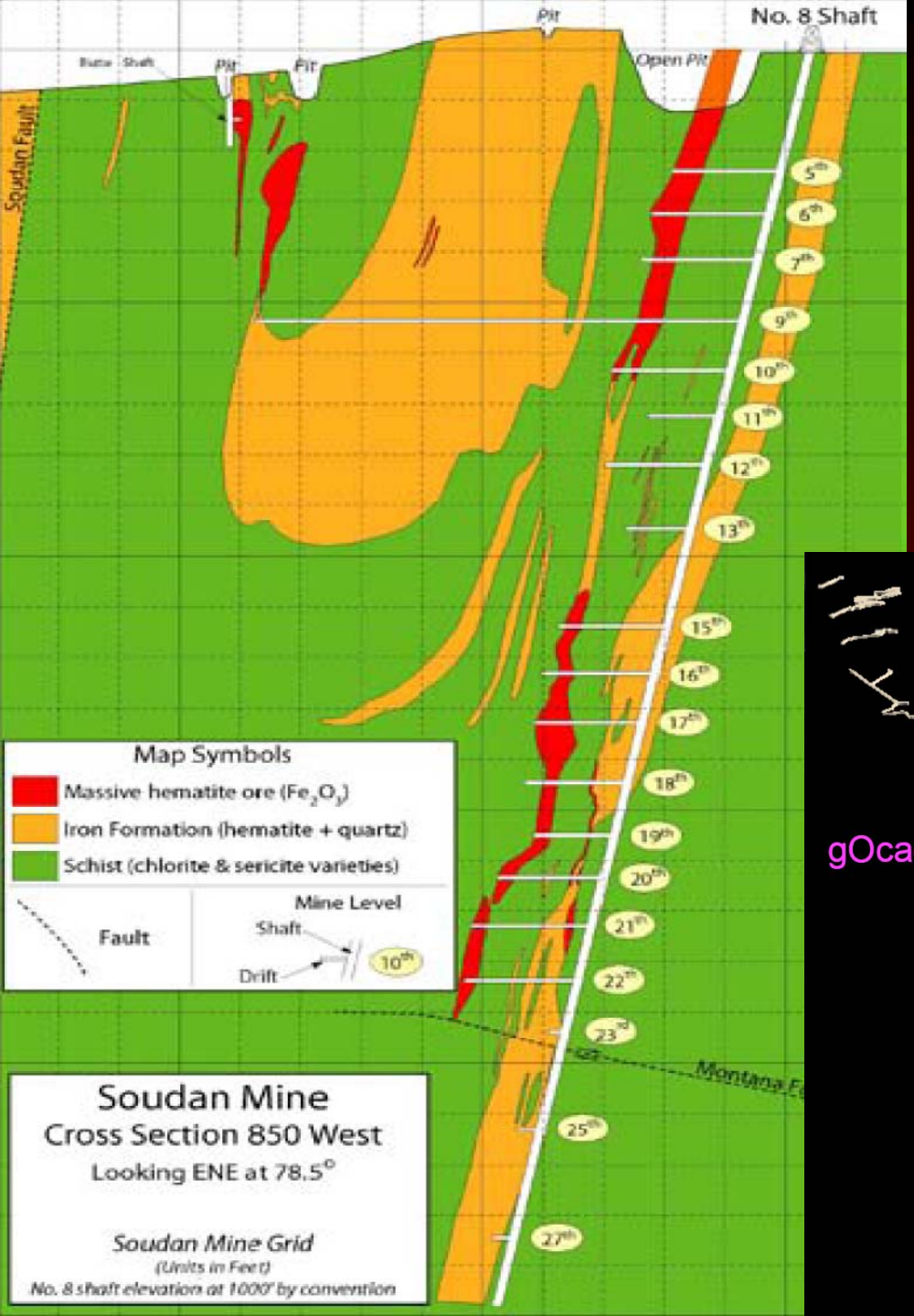
Deep (>1km) saline groundwater, common in the Canadian Shield

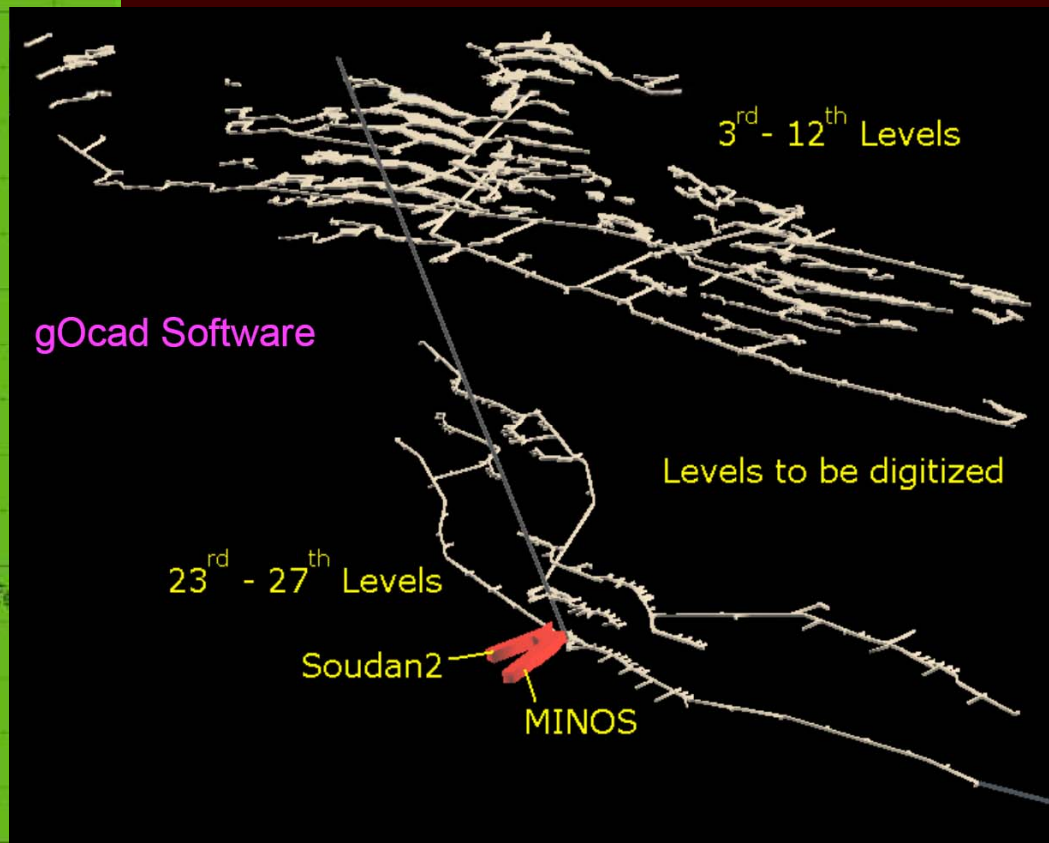
Plate 3: Bedrock Geologic Map of the Soudan Mine Area, St. Louis Co., NE Minnesota

Dean M. Peterson and Richard L. Patelke
Economic Geology Group, NRRI UMD
NRRI/TR-2003/29



Soudan Mine Cross-Section

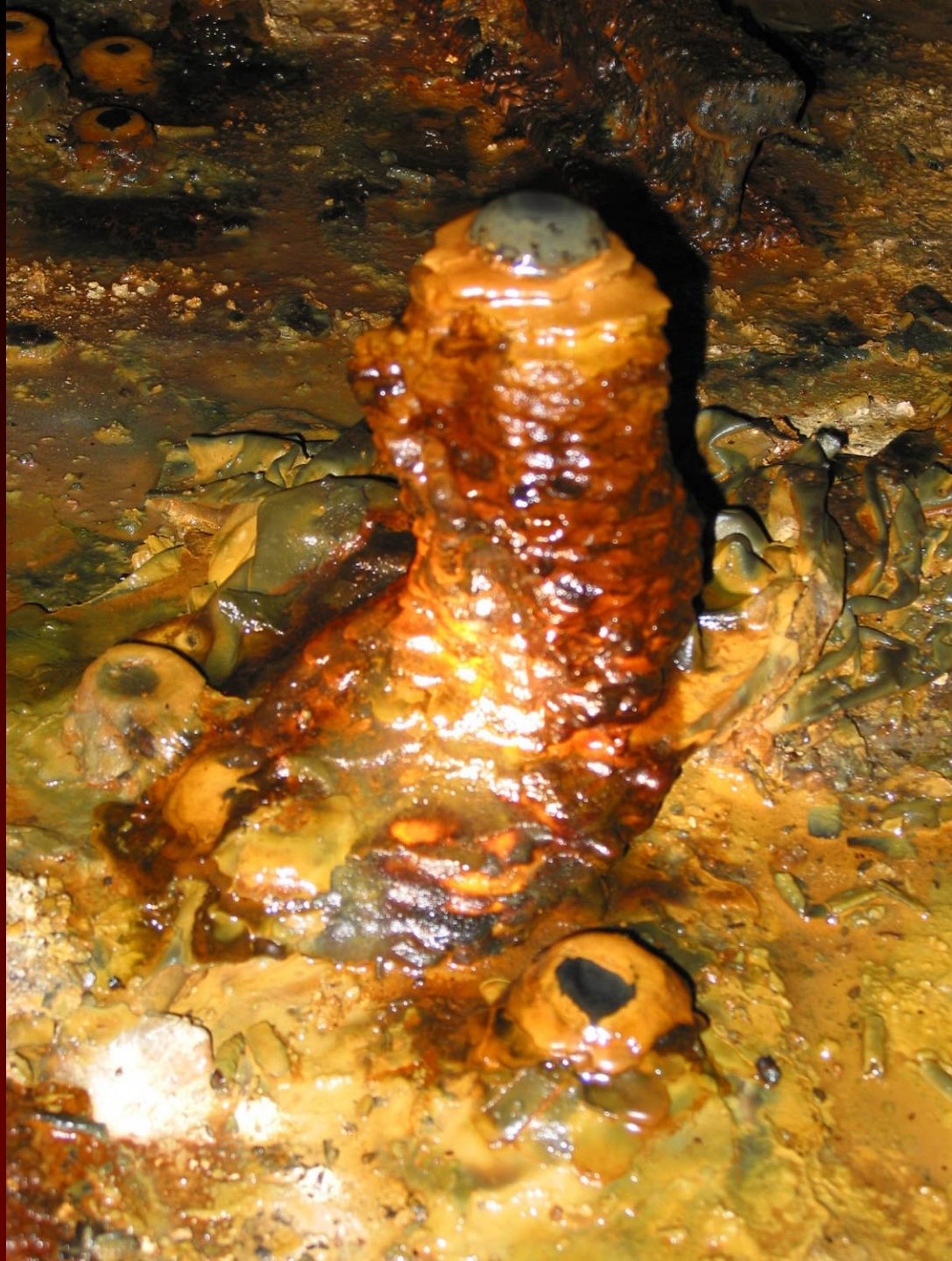





Cu, Ni, Zn, Co waters
10th Level

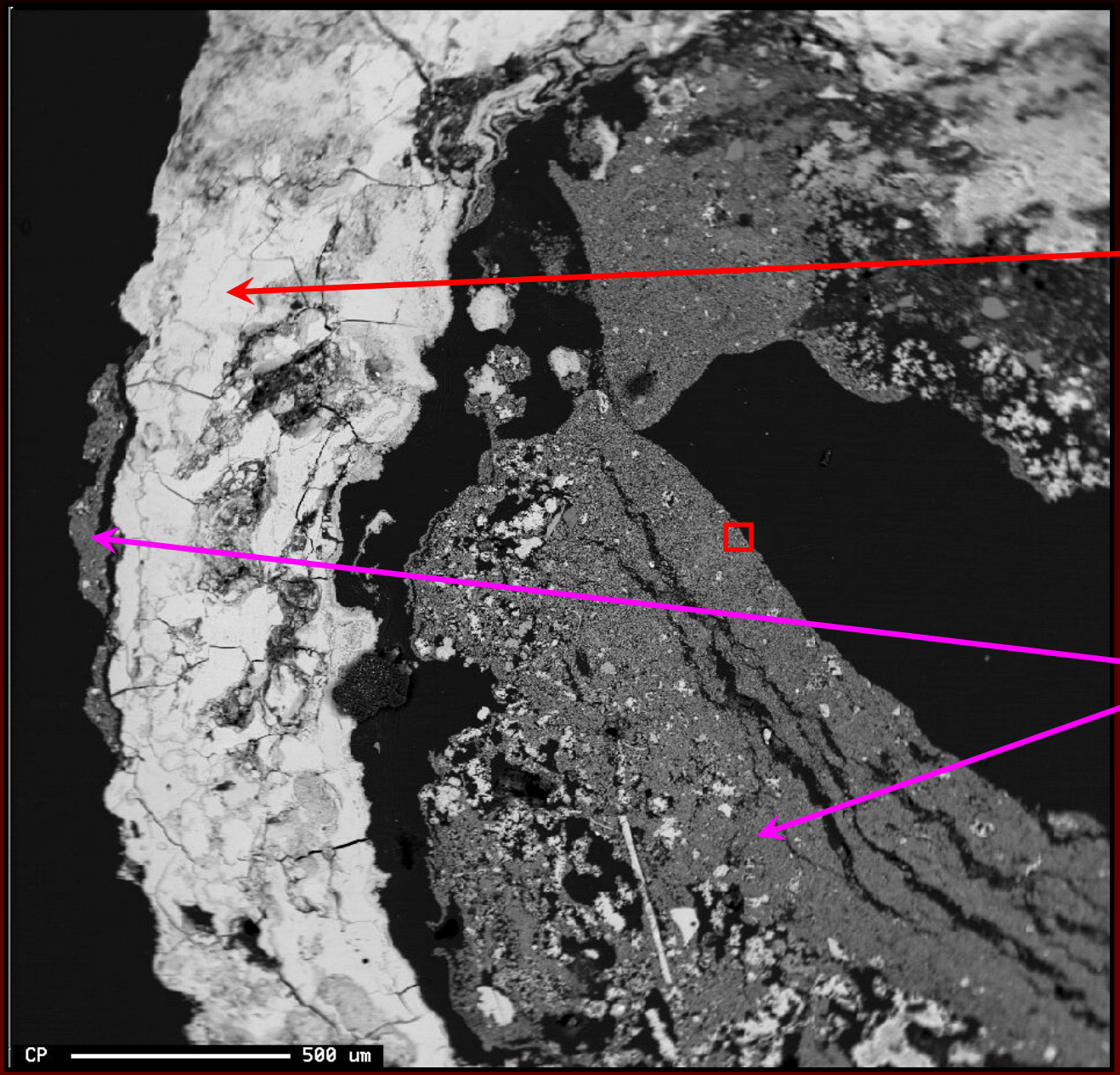
Stalagmite

23rd Level




Soda Straws
23rd Level
80% goethite
20% schwertmannite
trace magnetite

Level 23 Black Soda Straw



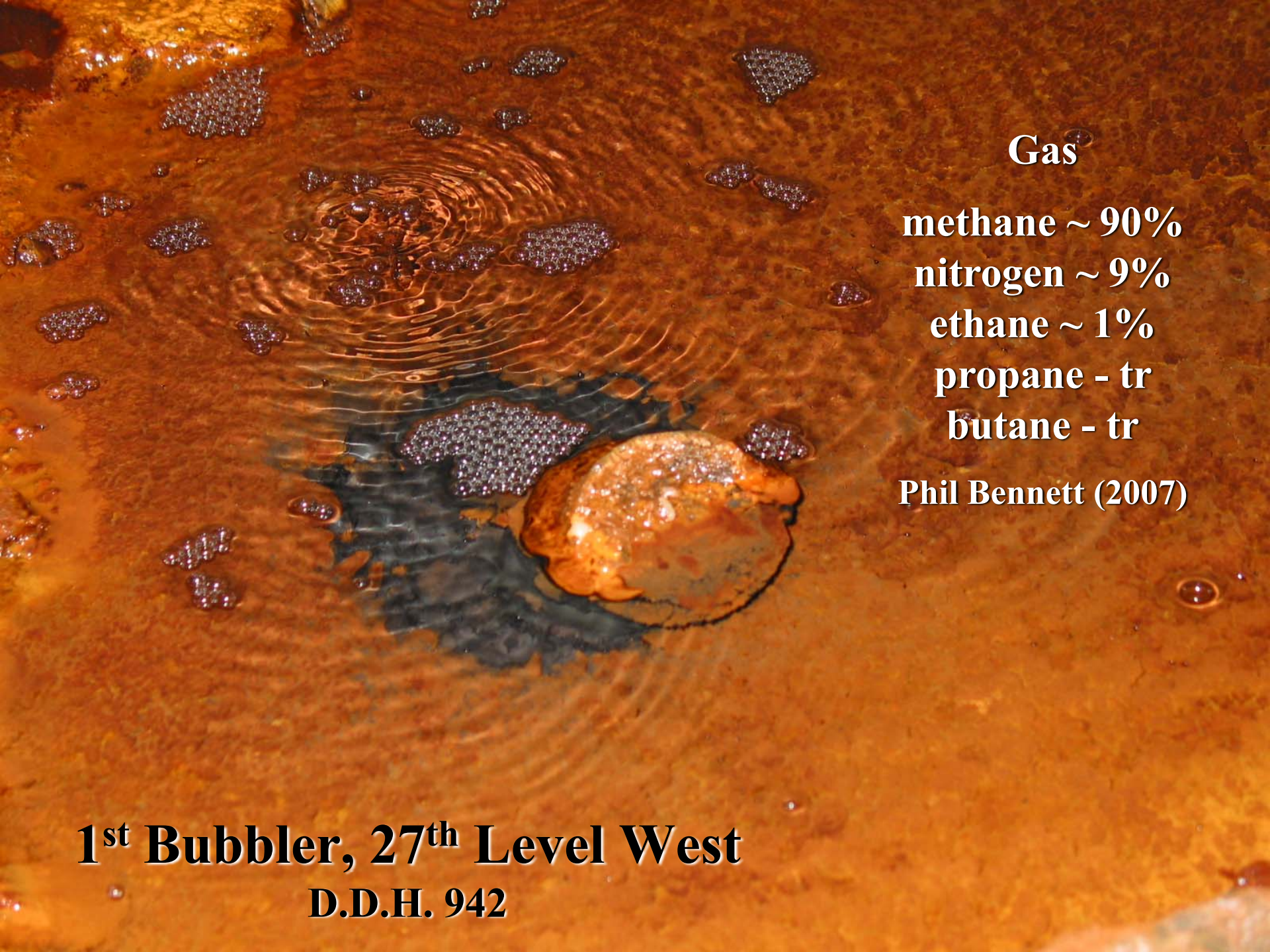
Iron Oxide
Fe, O

S, Fe, K , O

field of view 2.5 mm

1st Bubbler
27th Level West
D.D.H. 942

Ca-Mg-Na / Cl
Twice as salty as sea water
Very reducing water
Fe^{+2} rich
Rich Microbiology



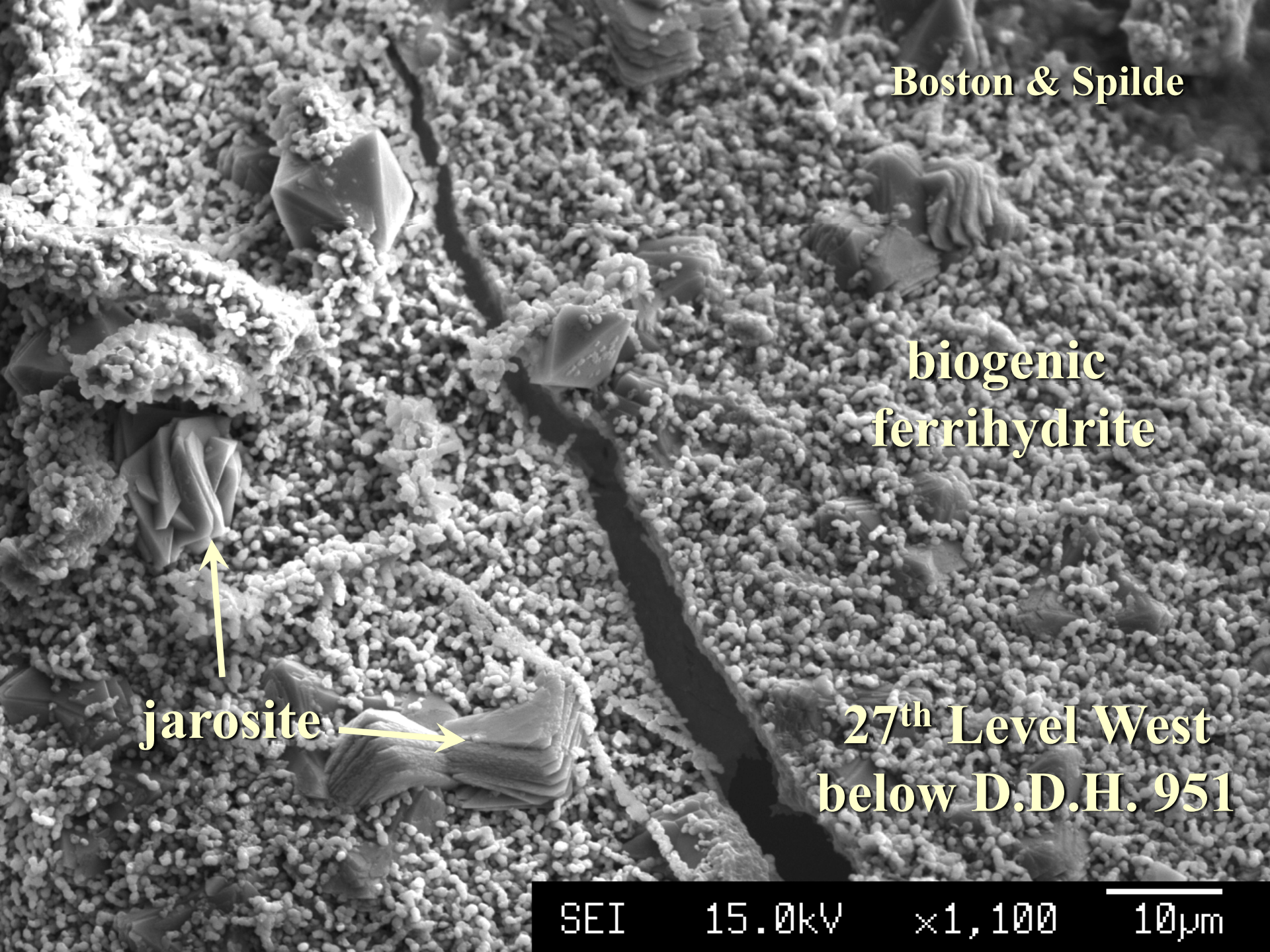
Gas

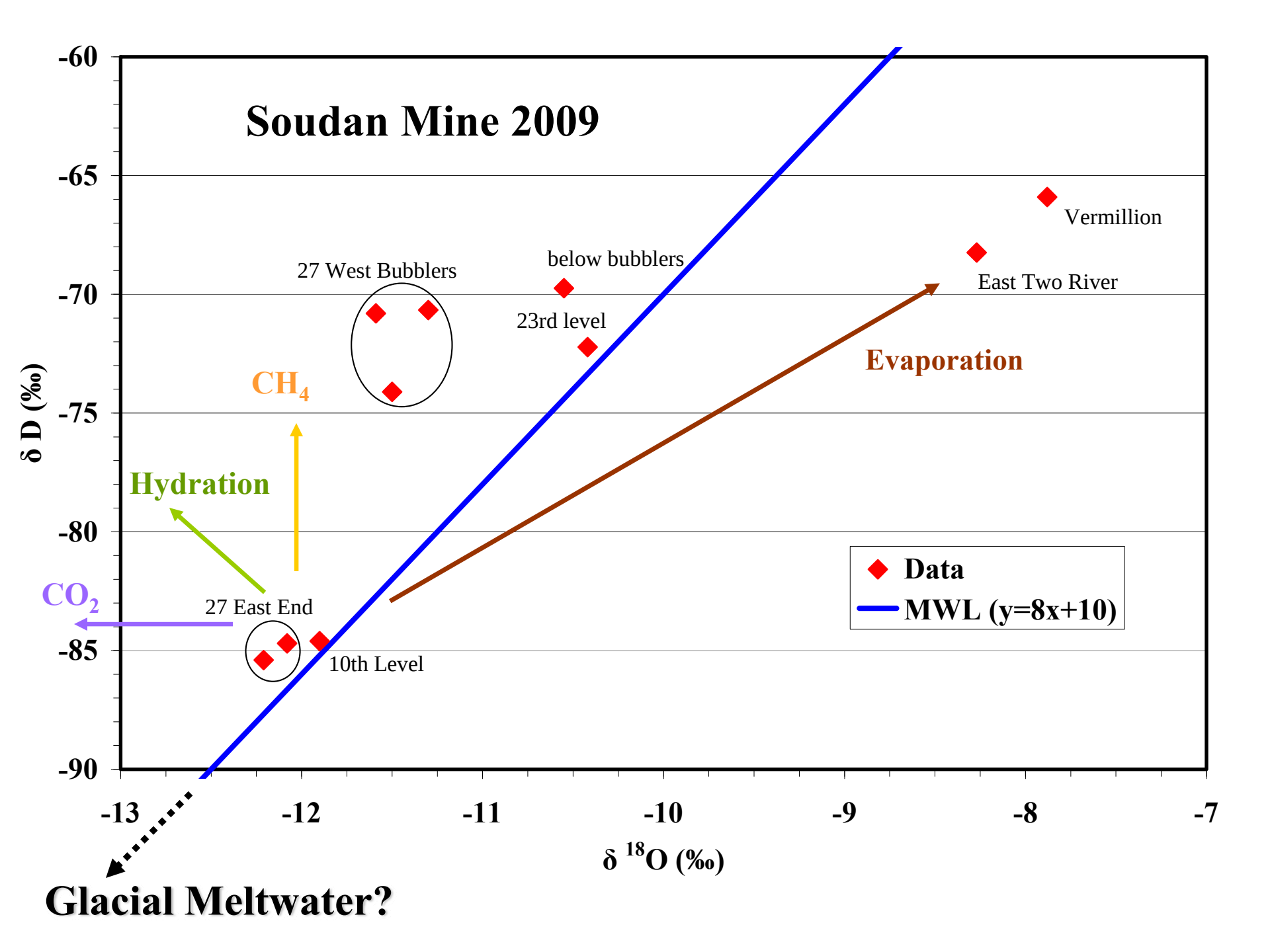
methane ~ 90%
nitrogen ~ 9%
ethane ~ 1%
propane - tr
butane - tr

Phil Bennett (2007)

1st Bubbler, 27th Level West

D.D.H. 942


Boston & Spilde
biogenic
ferrihydrite
jarosite
27th Level West
below D.D.H. 951
SEI 15.0kV ×1,100 10µm


Soudan Mine 2009
-60
-65
-70
-75
-80
-85
-90
δ D (‰)
-13
-12
-11
-10
-9
-8
-7
δ 18O (‰)
Vermillion
East Two River
below bubblers
23rd level
27 West Bubblers
Evaporation
CH4
Hydration
CO2
27 East End
10th Level
Data
MWL (y=8x+10)
Glacial Meltwater?


27th Level East
D.D.H. 963

Mammoth Hot Springs, Yellowstone

jaygoodrich-blog.com/blog_photos/yellow1.jpg

www.geraldearl.com/Photography/pictures/yellowstone/DSC_9316.jpg

guias-viajar.com

active flow areas are colored by microbiology

Lake Banda-Mir, Afghanistan

Lake Banda-Mir, Afghanistan

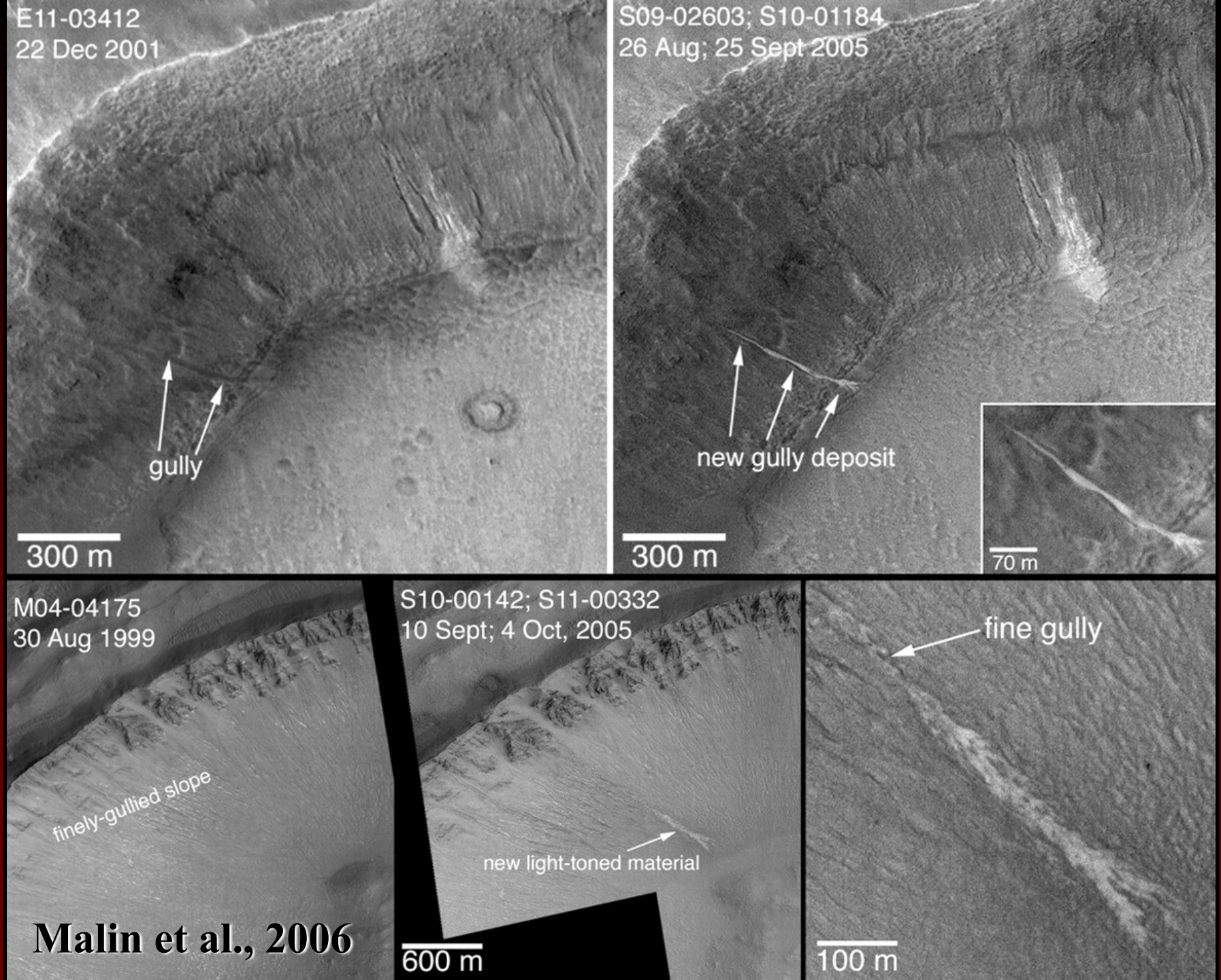

Rimstone Dams
in Soudan

Evidence for Recent Liquid Water on Mars

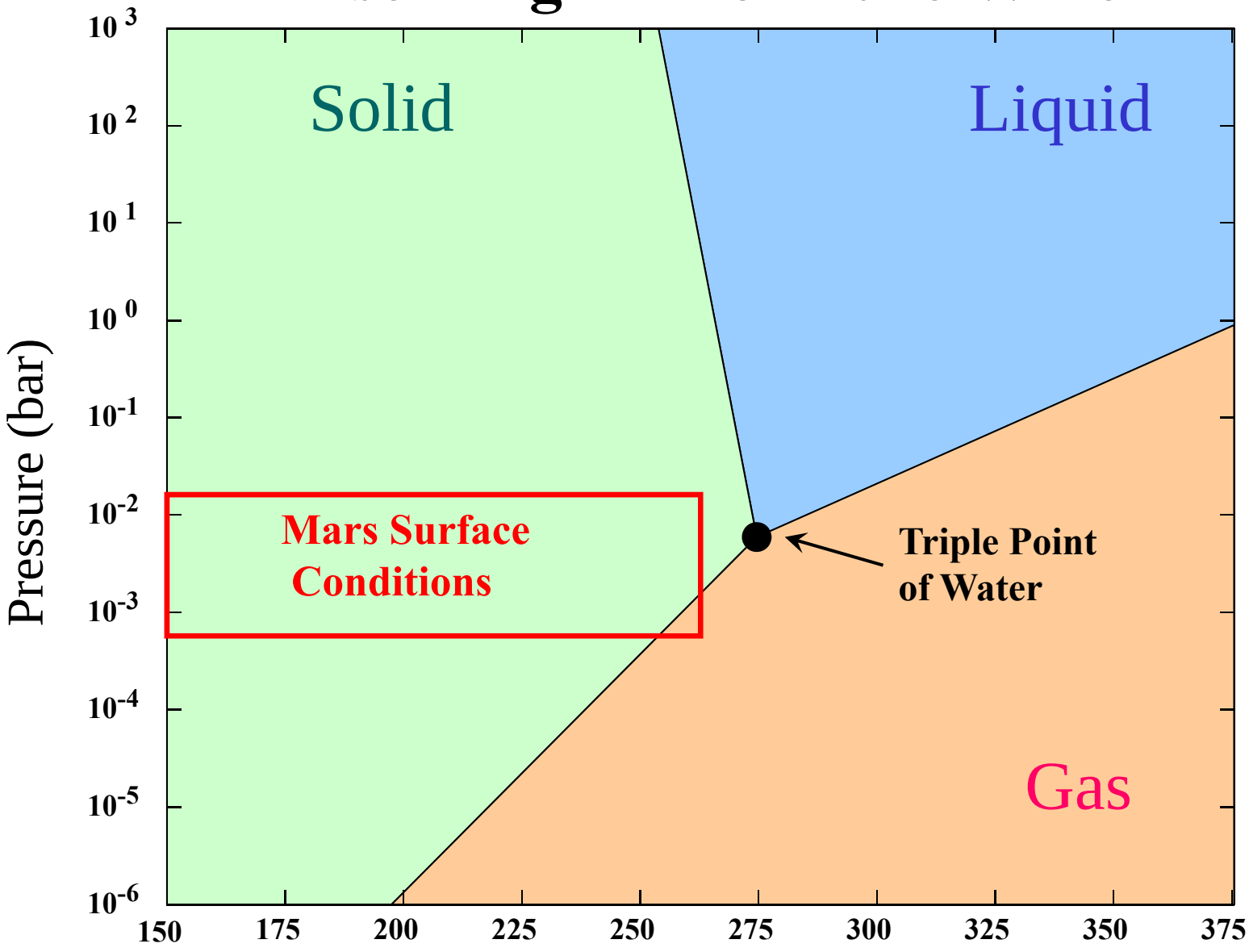
- Anastomosing channels
- Stream lined uplands
- Degraded terraces
- Abandoned spillways
- Regularly spaced rib-like bedforms

- Lack of craters on erosional features indicates young age

Baker (2001)

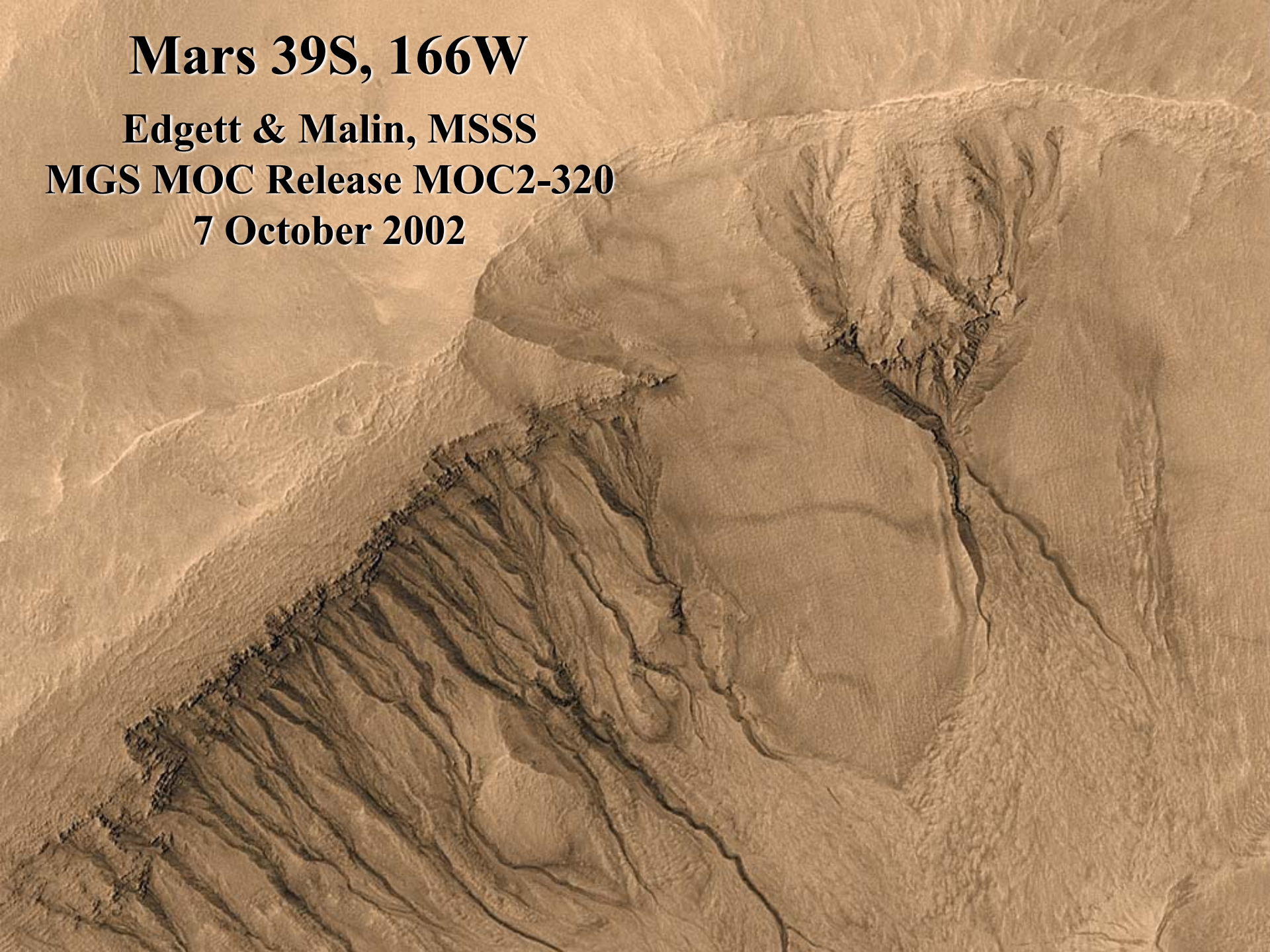

E11-03412
22 Dec 2001
gully
300 m
S09-02603; S10-01184
26 Aug; 25 Sept 2005
new gully deposit
300 m
70 m
M04-04175
30 Aug 1999
finely-gullied slope
S10-00142; S11-00332
10 Sept; 4 Oct, 2005
new light-toned material
600 m
fine gully
100 m
Malin et al., 2006

Phase Diagram for Pure Water

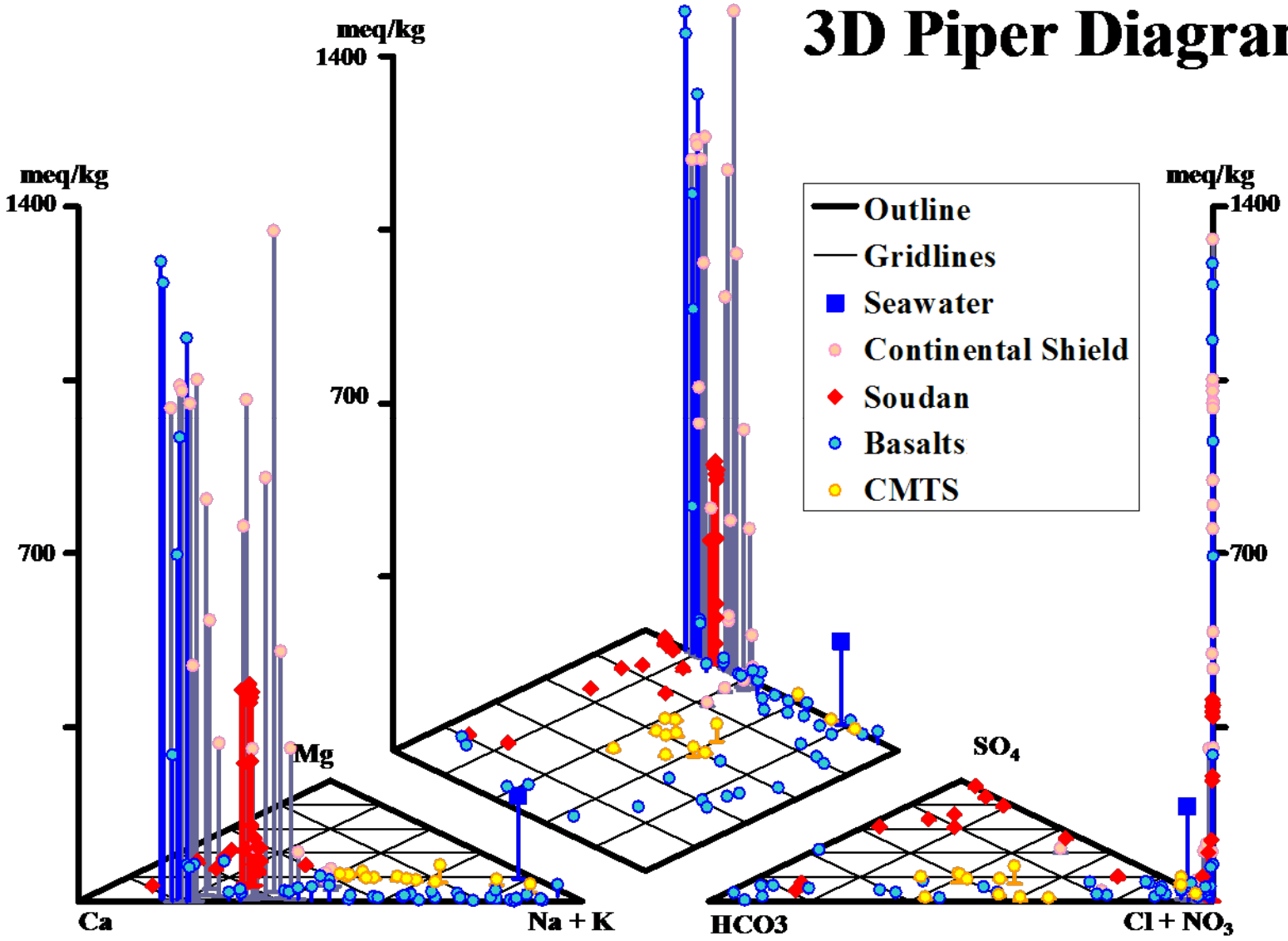


With thanks to Joe Mitchell

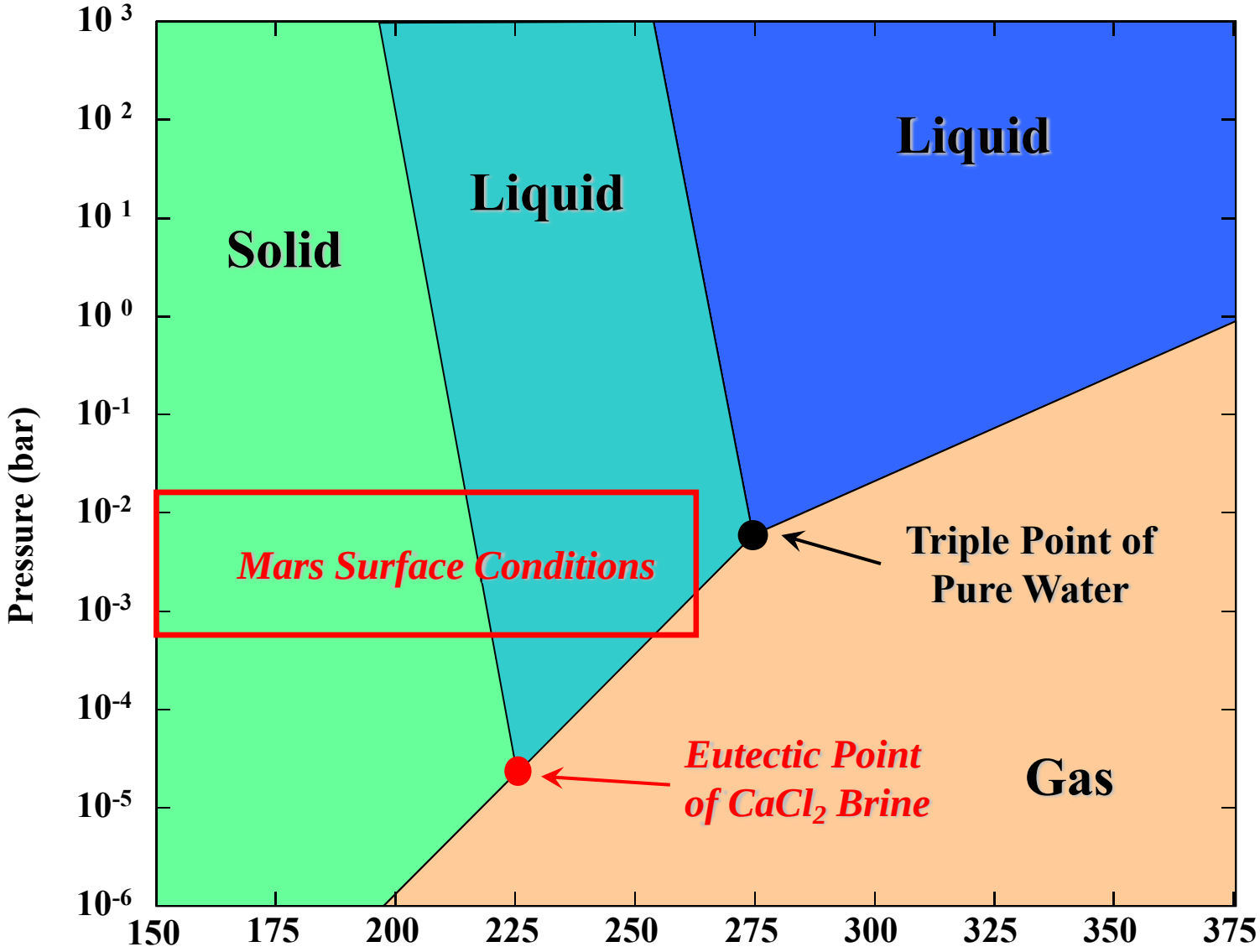
adapted from Bodnar (2001)


Mars 39S, 166W
Edgett & Malin, MSSS
MGS MOC Release MOC2-320
7 October 2002

Soudan Mine
3D Piper Diagram



Phase Diagram for Eutectic Brines



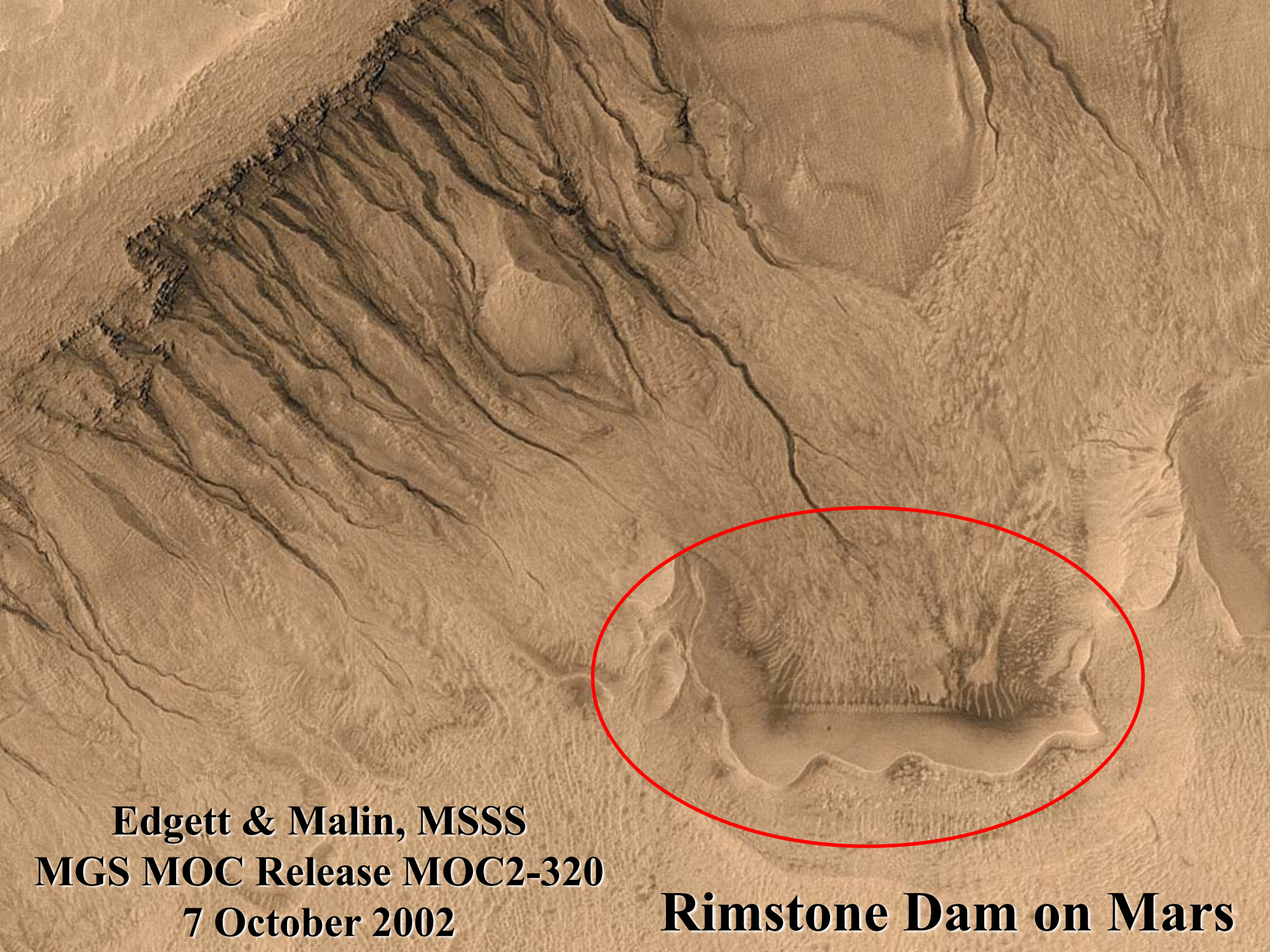
With thanks to Joe Mitchell

adapted from Bodnar (2001)

Don Juan Valley, Antarctica

Landsat 7 image

$CaCl_2$ brines liquid to –52 °C



Edgett & Malin, MSSS
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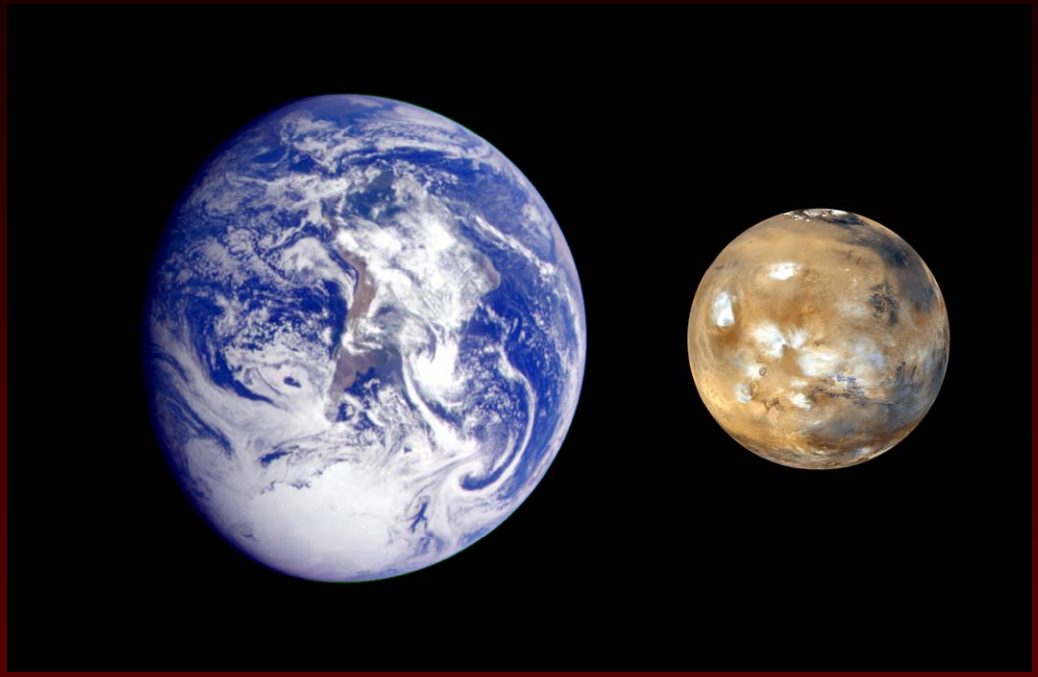
Rimstone Dam on Mars

The Earth and Mars



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!**

The Big Picture - Microbial Ecology

The microbial world is not really a good expression. It is not a world, it's not a planet, or a constellation. It's not even a universe, for there are **1,000,000,000** times more bacteria in the world than stars in the sky.

Imagine the microbial 'world' as a **billion universes** each made of thousands or **millions of galaxies** and you have some idea of the scale of the challenge of microbial ecology.

Tom Curtis
University of Newcastle upon Tyne
(Env. Microbiol. 2007, 9(1), 1-11)

Hubble Deep Space View

Level 27 of the Soudan Iron Mine
A Microbial Galaxy

We have looked at this galaxy in two ways:

1) An individual star

- Cultivation and characterization of *Marinobacter*

2) A snapshot of the entire galaxy

- Environmental DNA sequencing

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Level 27 of the Soudan Iron Mine

A Microbial Galaxy

- There is an incredible diversity of bacteria on our planet.
- The VAST majority of these bacteria have never been cultivated (~ 99%).
- Cultivation is *nearly* essential in order to understand how bacteria are able to catalyze reactions of interest.
- One way to begin understanding the impact / abilities of bacteria from the Soudan Mine is to cultivate a representative organism from one of the most extreme environments present in the mine - ***the Level 27 brine***.

Isolation of Bacteria from the Level 27 Brine

Strain JG228

Bacteria have been cultivated from the level 27 brine near two vertical boreholes.

All isolates (6/6) were identified as belonging to the genus *Marinobacter.*

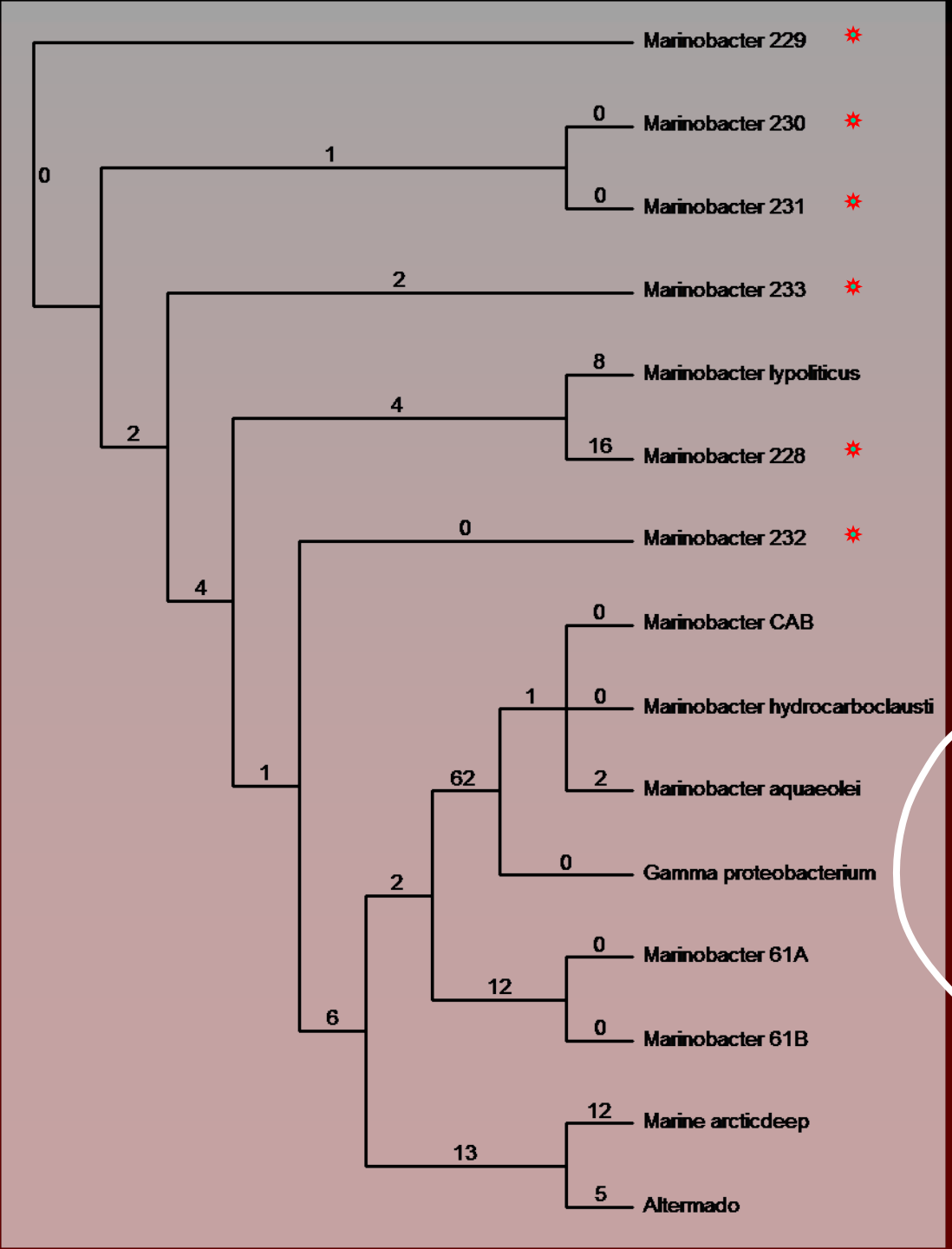
Marinobacter is commonly found in oceans.

Are these bacteria remnants from an ancient ocean?!

Some species are able to oxidize ferrous iron, a metabolism we would predict to be occurring in the iron-rich brine.

R. Lesniewski and J. Gralnick

Phylogentic Tree



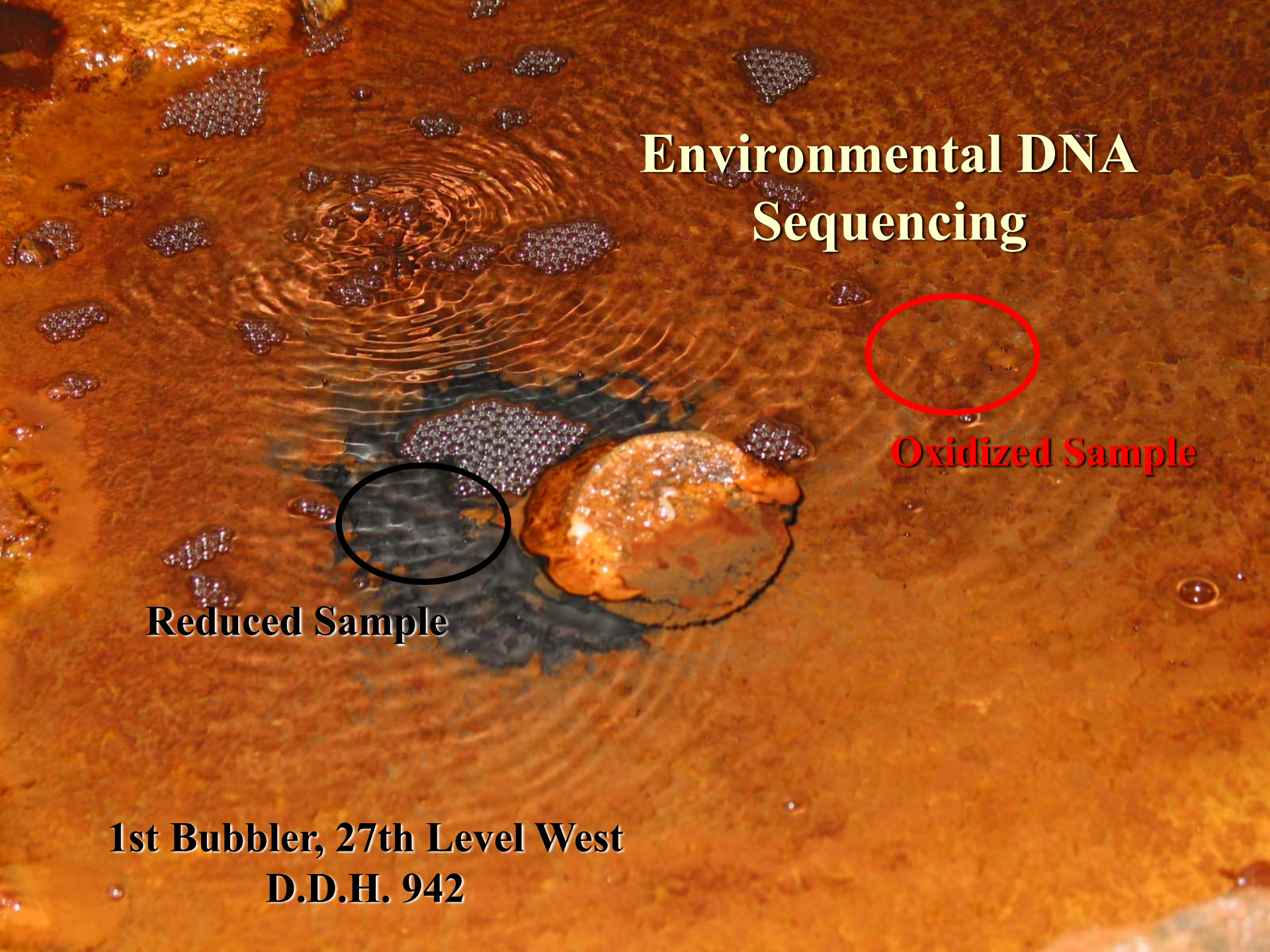
Tree based on 16s rRNA gene sequence of Soudan brine isolates and known ***Marinobacter*** strains.

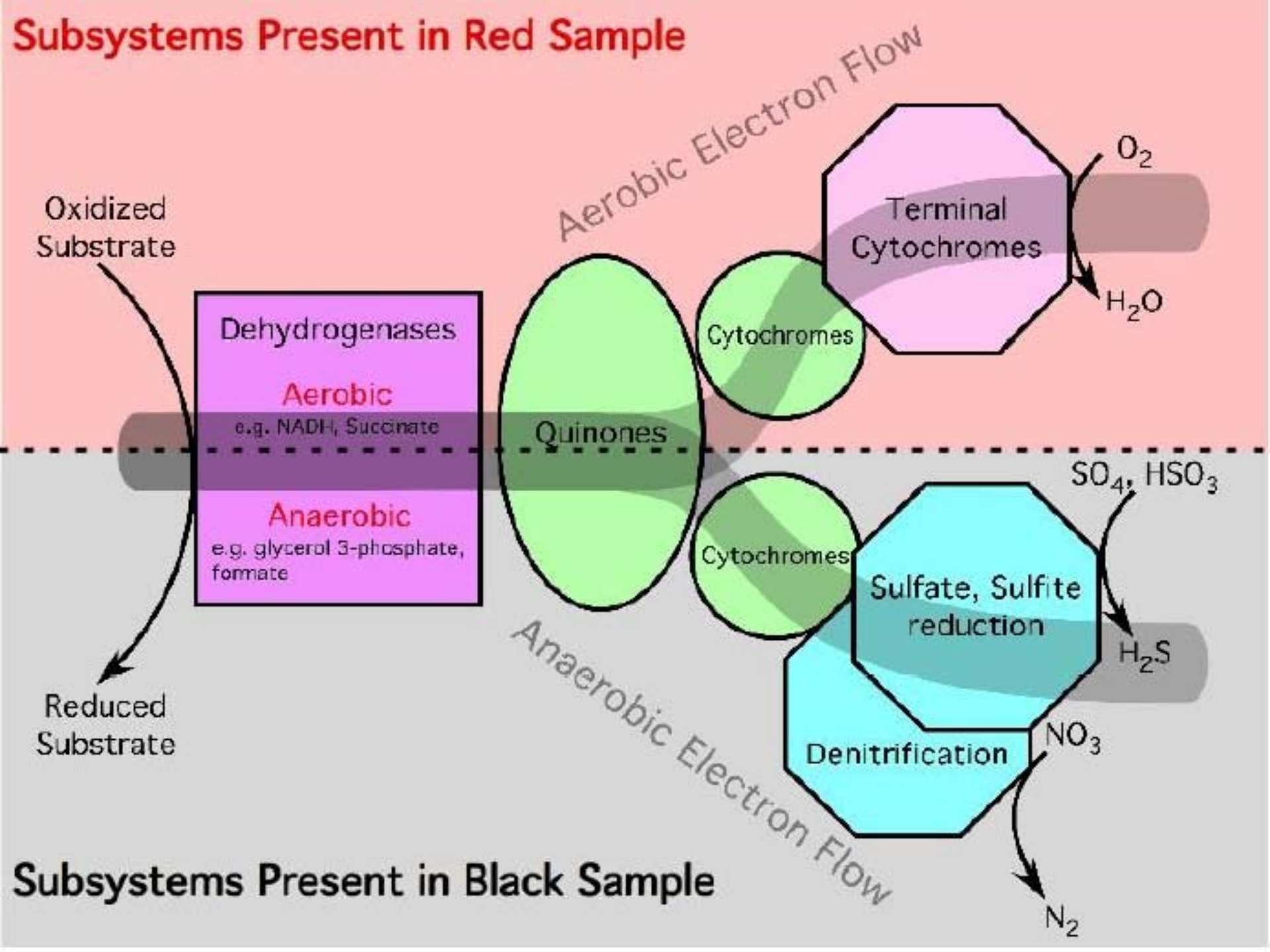
Ocean *Marinobacter* appear to be derived from Soudan *Marinobacter*

Strains 228, 229 and 230 were isolated from the 1st bubbler.

Strains 231, 232 and 233 were isolated from the 2nd bubbler.

R. Lesniewski and J. Gralnick


Environmental DNA Sequencing
Oxidized Sample
Reduced Sample
1st Bubbler, 27th Level West
D.D.H. 942


Subsystems Present in Red Sample
Aerobic Electron Flow
Oxidized Substrate
Dehydrogenases
Aerobic
e.g. NADH, Succinate
Anaerobic
e.g. glycerol 3-phosphate, formate
Quinones
Cytochromes
Terminal Cytochromes
O_2
H_2O
Reduced Substrate
Cytochromes
Sulfate, Sulfite reduction
SO_4, HSO_3
H_2S
Denitrification
NO_3
N_2
Anaerobic Electron Flow
Subsystems Present in Black Sample

Why Soudan?

Metals = Energy = Life

This ancient Banded Iron Formation provides the appropriate redox gradients for life to *thrive*.

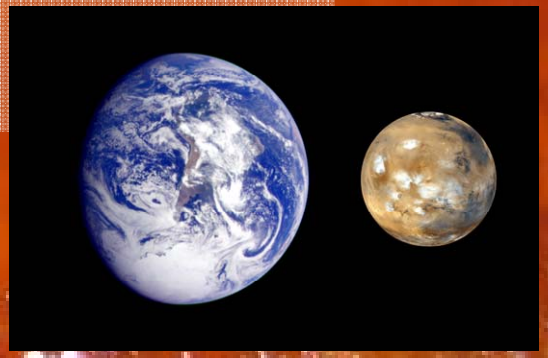
This ecosystem is *independent* of surface processes.

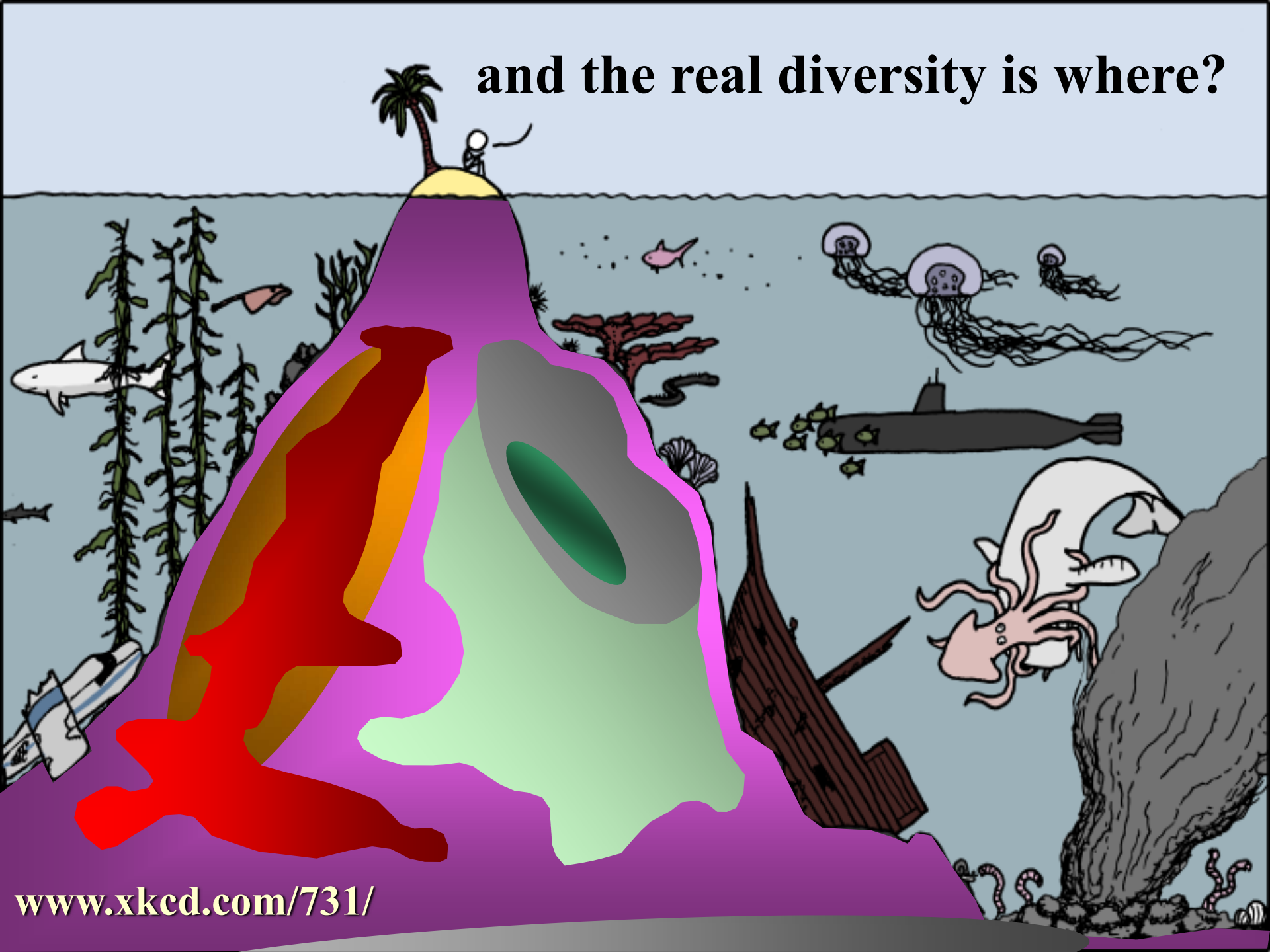
- No photosynthesis input (unlike in marine systems)
- Very little (if any) mixing with surface waters
- "Yellowstone of the Subsurface"

Representative of some of the earliest forms of life.

- Slow metabolic rates means the microbes present are fossil forms of surface organisms

If there is life on Mars today, *this* is what it would probably look like.




and the real diversity is where?
www.xkcd.com/731/