How convection, electrons, protons and photons drove the first microbes into being

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Microbiology Society 2017 Edinburgh

Jet Propulsion Laboratory, California Institute of Technology

US Government sponsorship acknowledged

ON

GROWTH AND FORM

BY

D'ARCY WENTWORTH THOMPSON

Cambridge :

at the University Press

1917

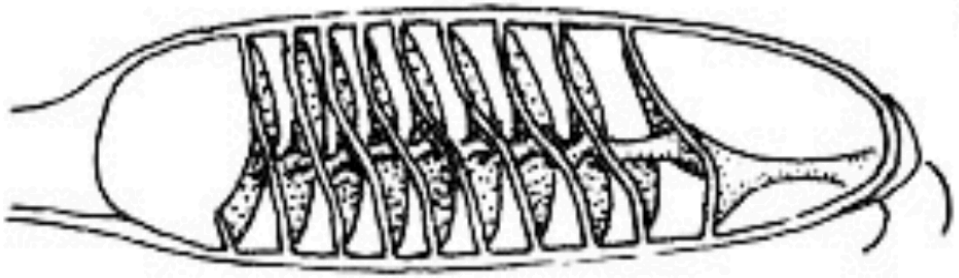
A deal of evolution is involved in keeping due balance between surface and mass as growth goes on …

of these …

the helicoid spiral is the most interesting to the biologist

… e.g.,

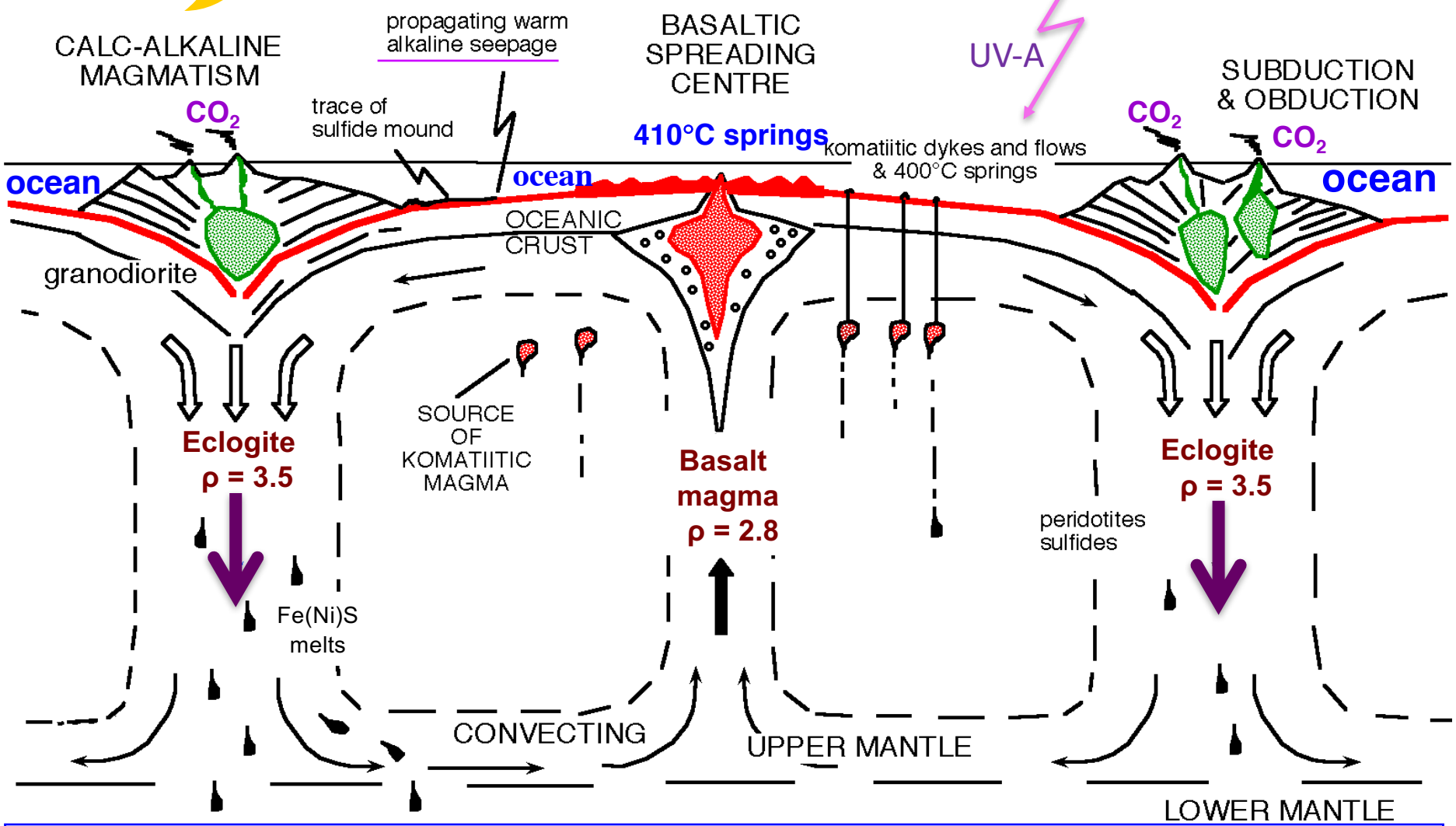
the "spiral valve" of the shark's gut



Autocatalytic mantle convection engine at 4.4Ga

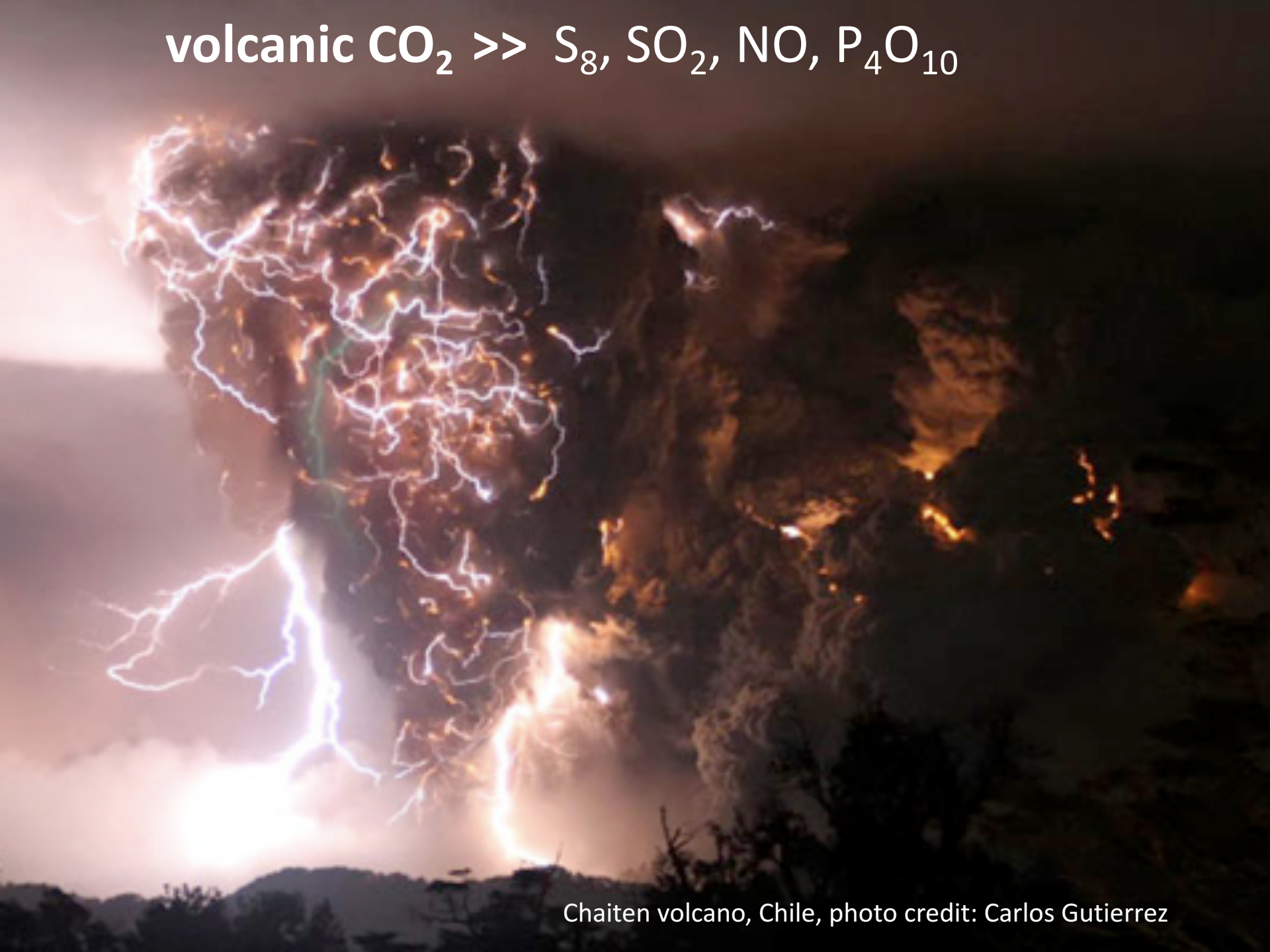
It's engines all the way down

1 - 10 bars of CO_2

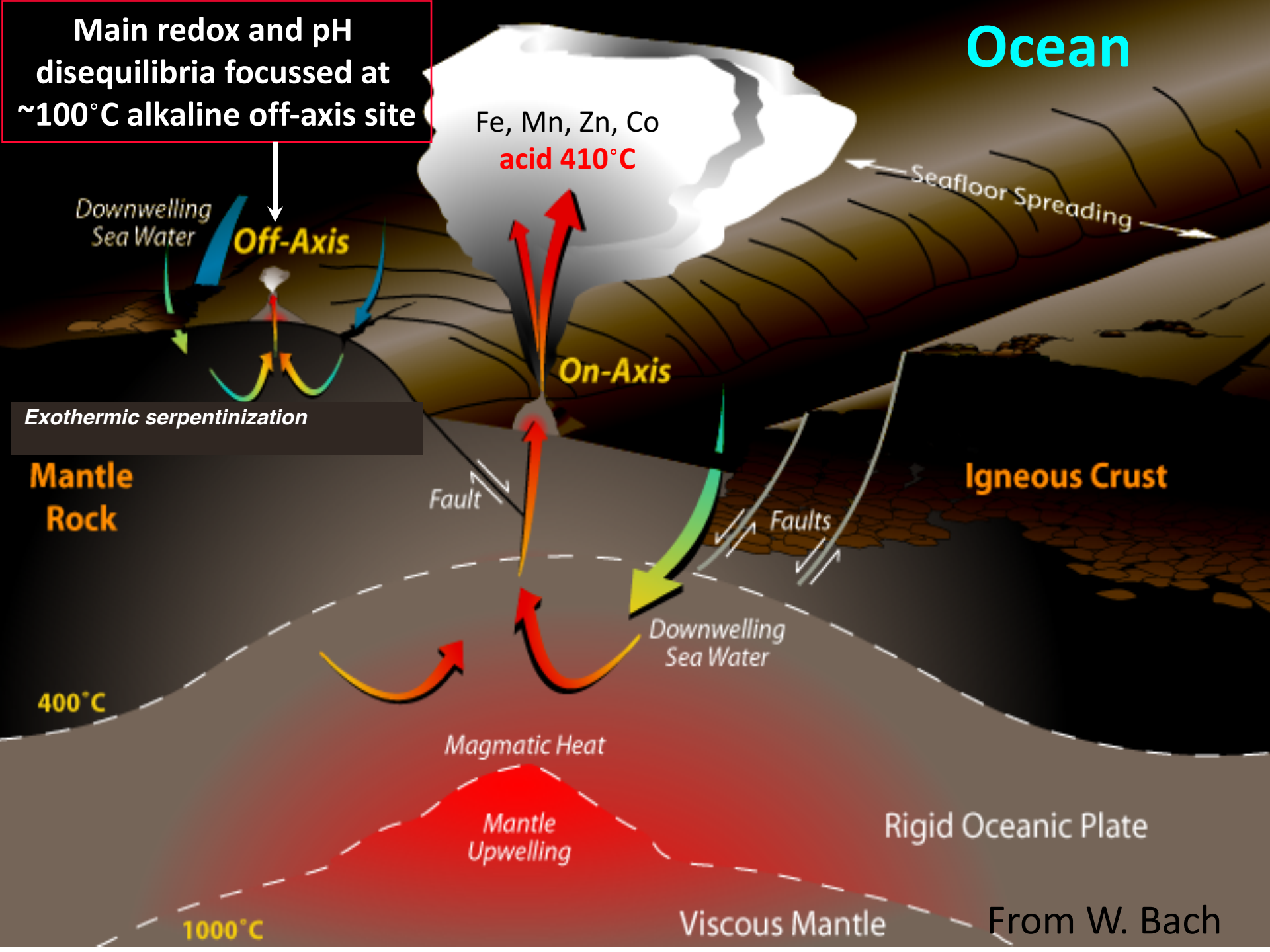


Russell & Hall 2006 GSA Mem192, 1-32, after Holmes 1931 Trans Geol Soc Glasgow 18, 559

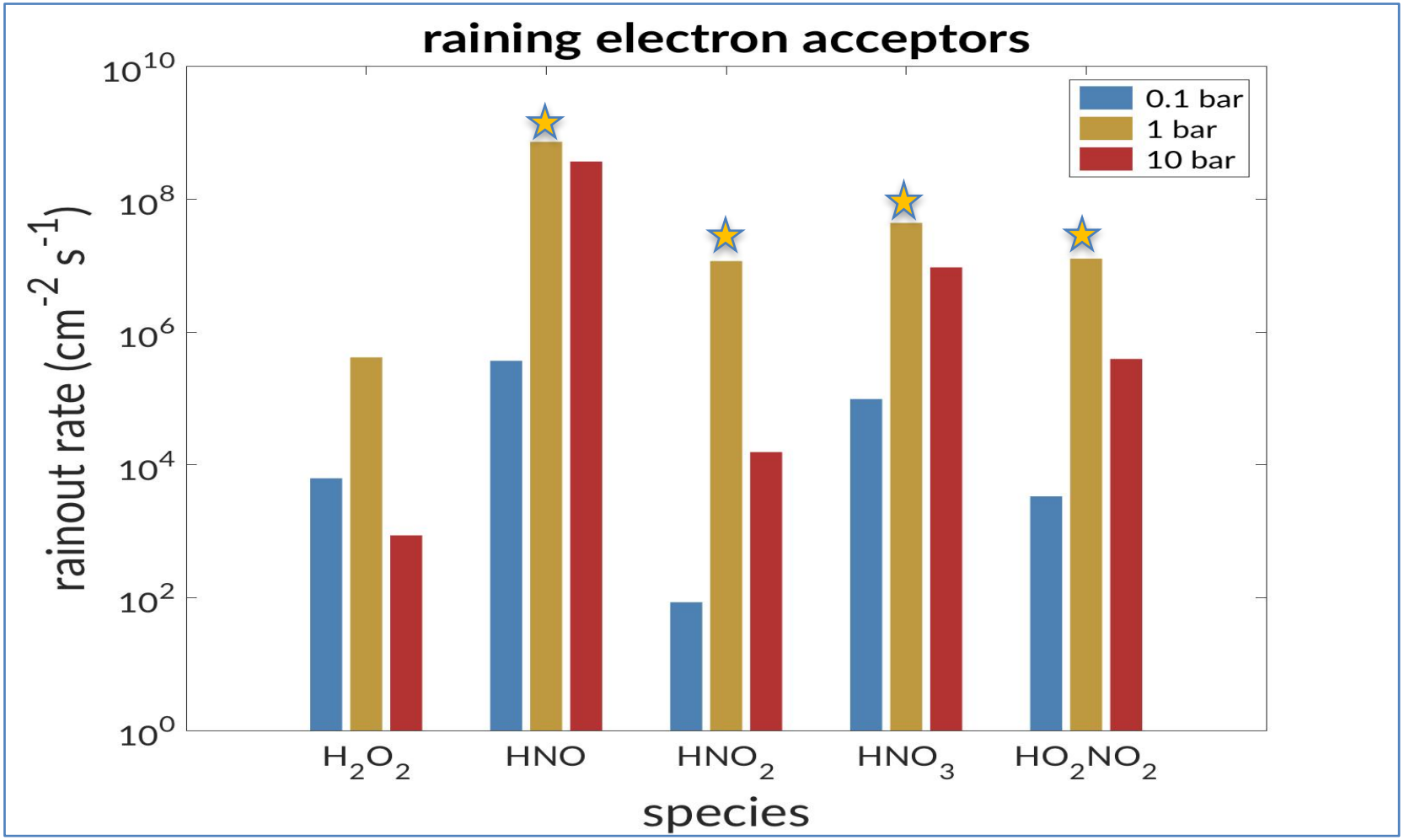
volcanic CO_2 >> S_8, SO_2, NO, P_4O_{10}



Chaiten volcano, Chile, photo credit: Carlos Gutierrez

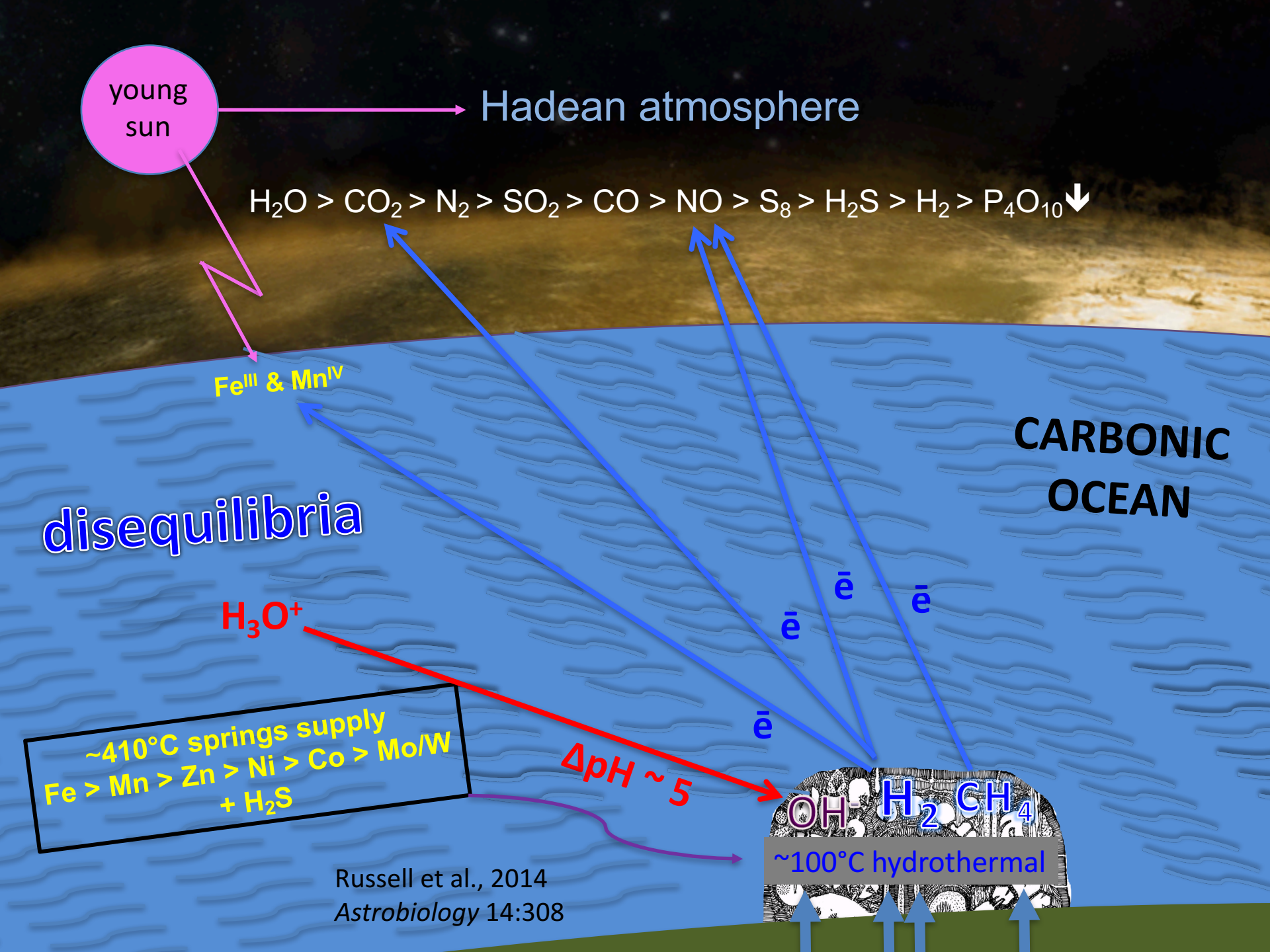

Main redox and pH disequilibria focussed at ~100˚C alkaline off-axis site
Ocean
Fe, Mn, Zn, Co
acid 410˚C
Seafloor Spreading
Downwelling Sea Water
Off-Axis
On-Axis
Exothermic serpentinization
Mantle Rock
Fault
Faults
Igneous Crust
Downwelling Sea Water
400˚C
Magmatic Heat
Mantle Upwelling
Rigid Oceanic Plate
1000˚C
Viscous Mantle
From W. Bach

1 bar CO_2 favors



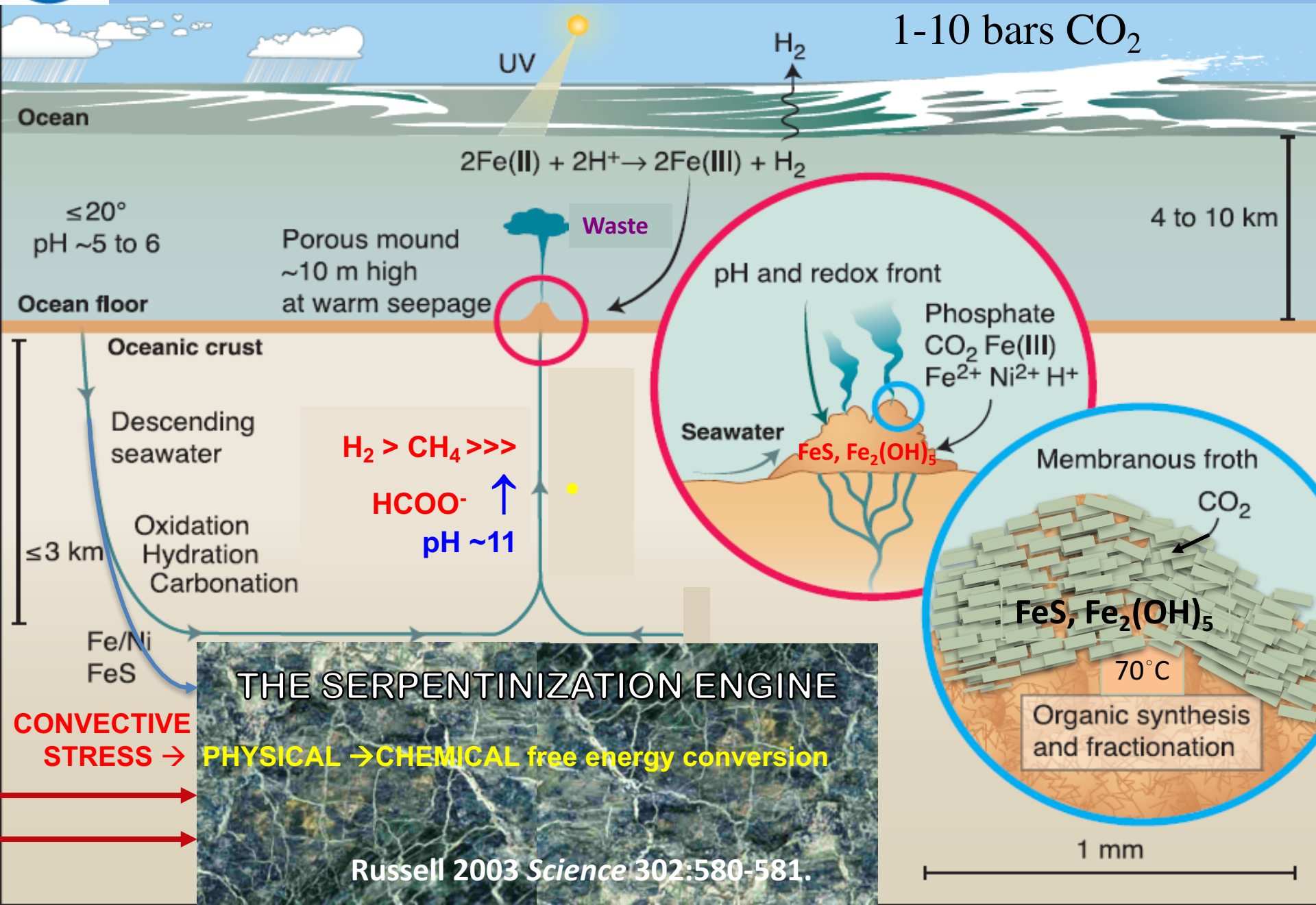
Rainout of NOx → micromolar concentration of nitrate at steady state

Wong, Charnay, Gao, Yung, Russell, 2017. *Astrobiology* in press



Russell et al., 2014
Astrobiology 14:308

Serpentinization → H_2 > CH_4 + $[FeO(OH)(MoS_4)_2]^{3-}$



Fe-mound formation [~$Fe_2(OH)_5$ > FeS_{1+x}] in a low-temperature hydrothermal system at the Jan Mayen Vent Fields

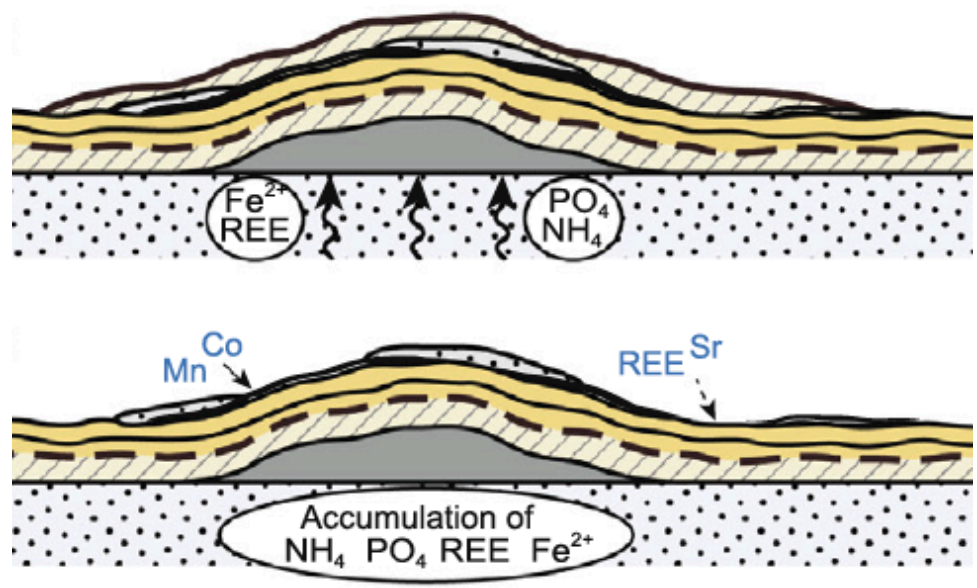
Johannessen et al. 2017 Geochim Cosmochim Acta 202:101-123.

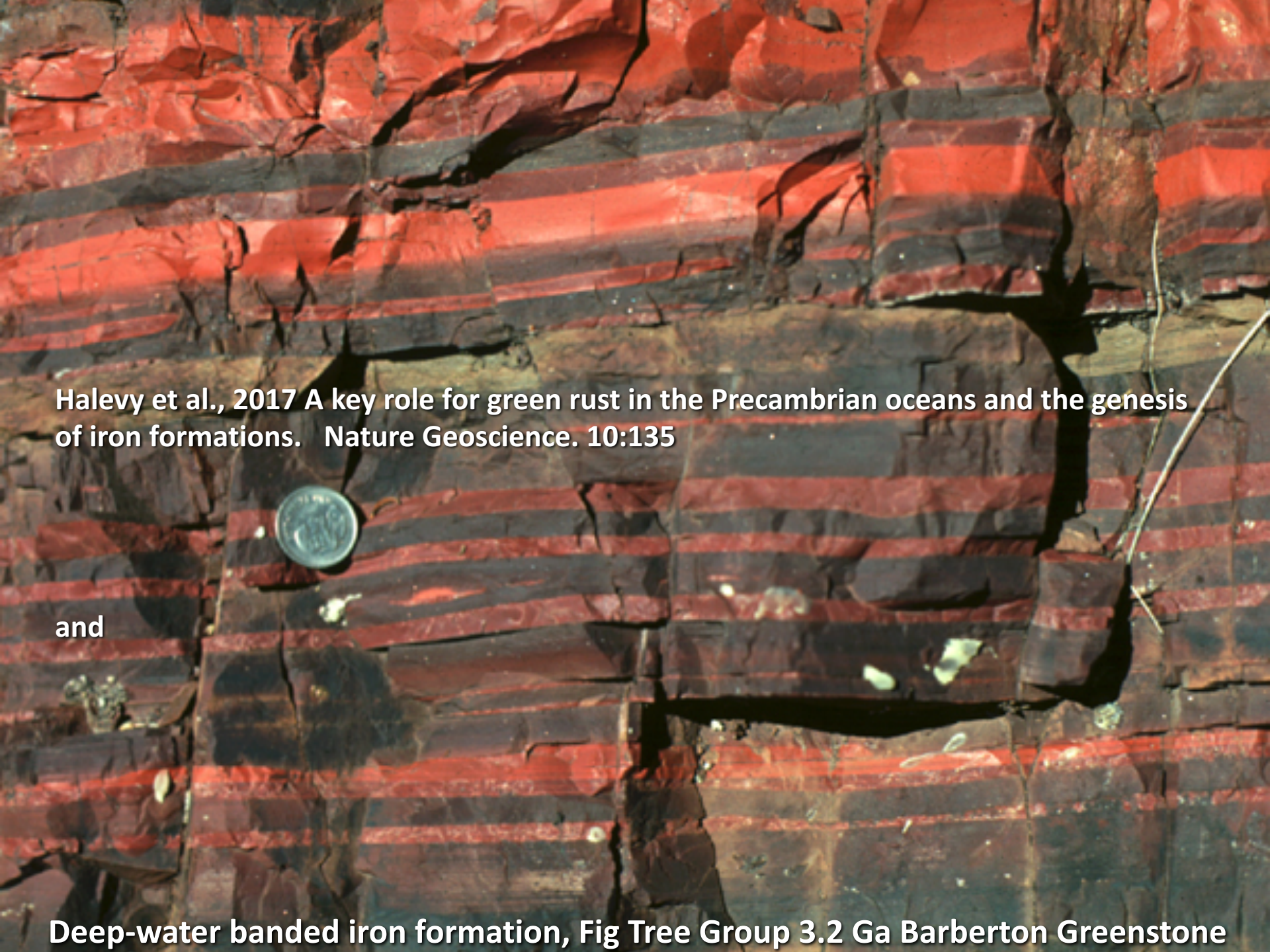
cf

Fe-Si-oxyhydroxide deposits at The Lilliput Hydrothermal Field

Dekov et al. 2010 Chem Geol 278:186–200

The Troll Wall field



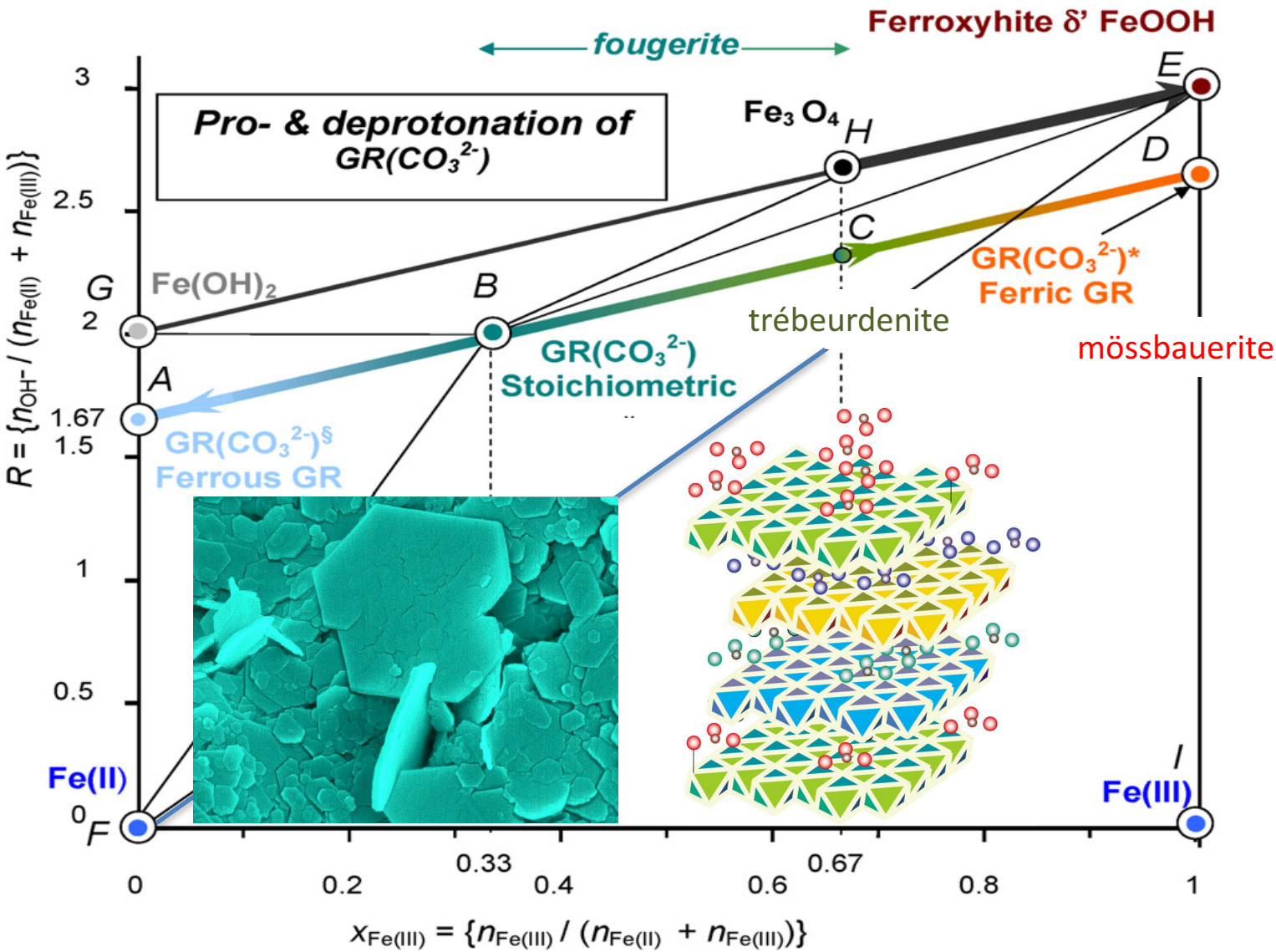


Halevy et al., 2017 A key role for green rust in the Precambrian oceans and the genesis of iron formations. Nature Geoscience. 10:135

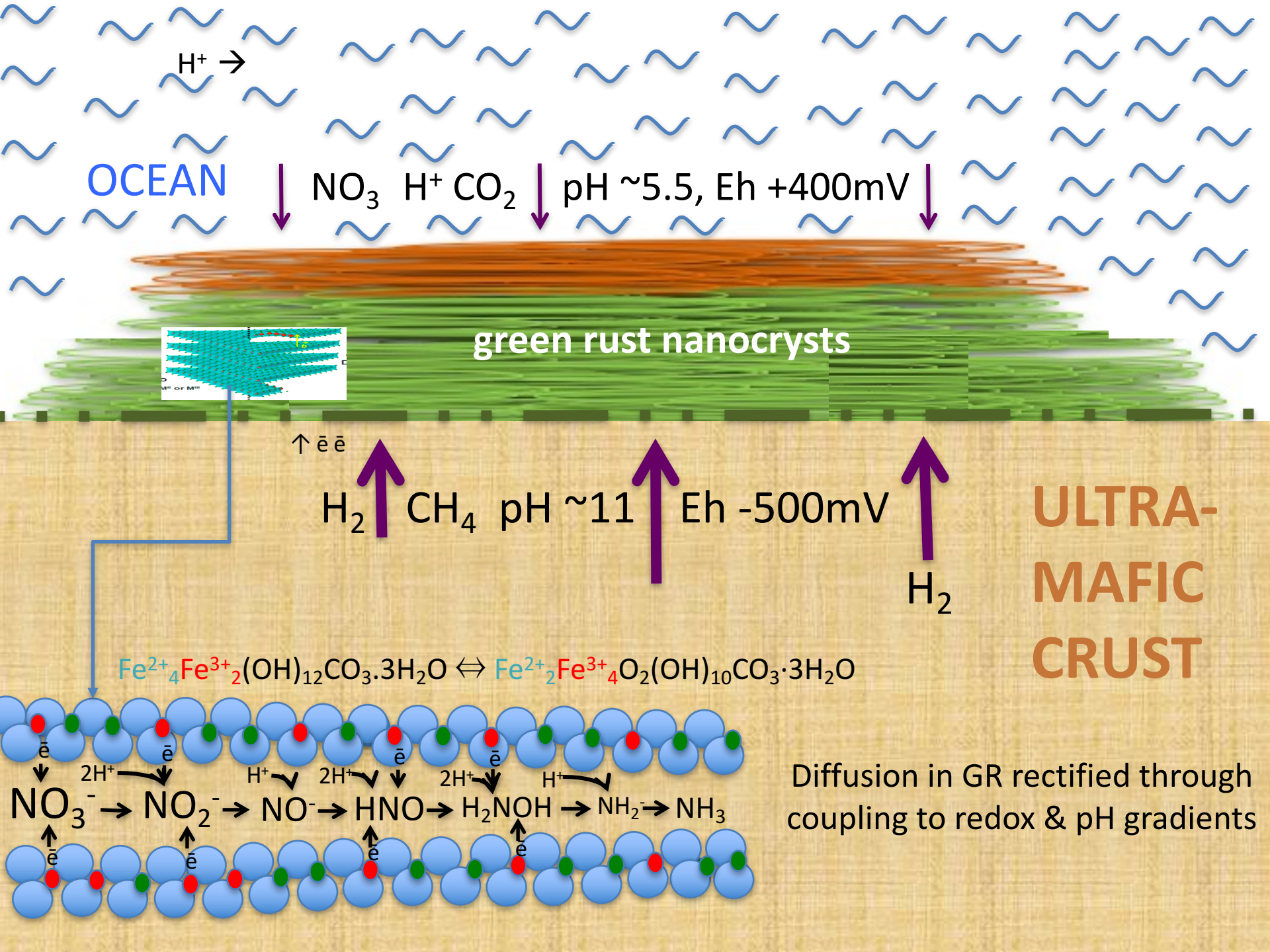
and

Deep-water banded iron formation, Fig Tree Group 3.2 Ga Barberton Greenstone

fougèrite $Fe^{2+}_4Fe^{3+}_2(OH)_{12}CO_3.3H_2O$ → trébeurdenite $Fe^{2+}_2Fe^{3+}_4O_2(OH)_{10}CO_3{\cdot}3H_2O$

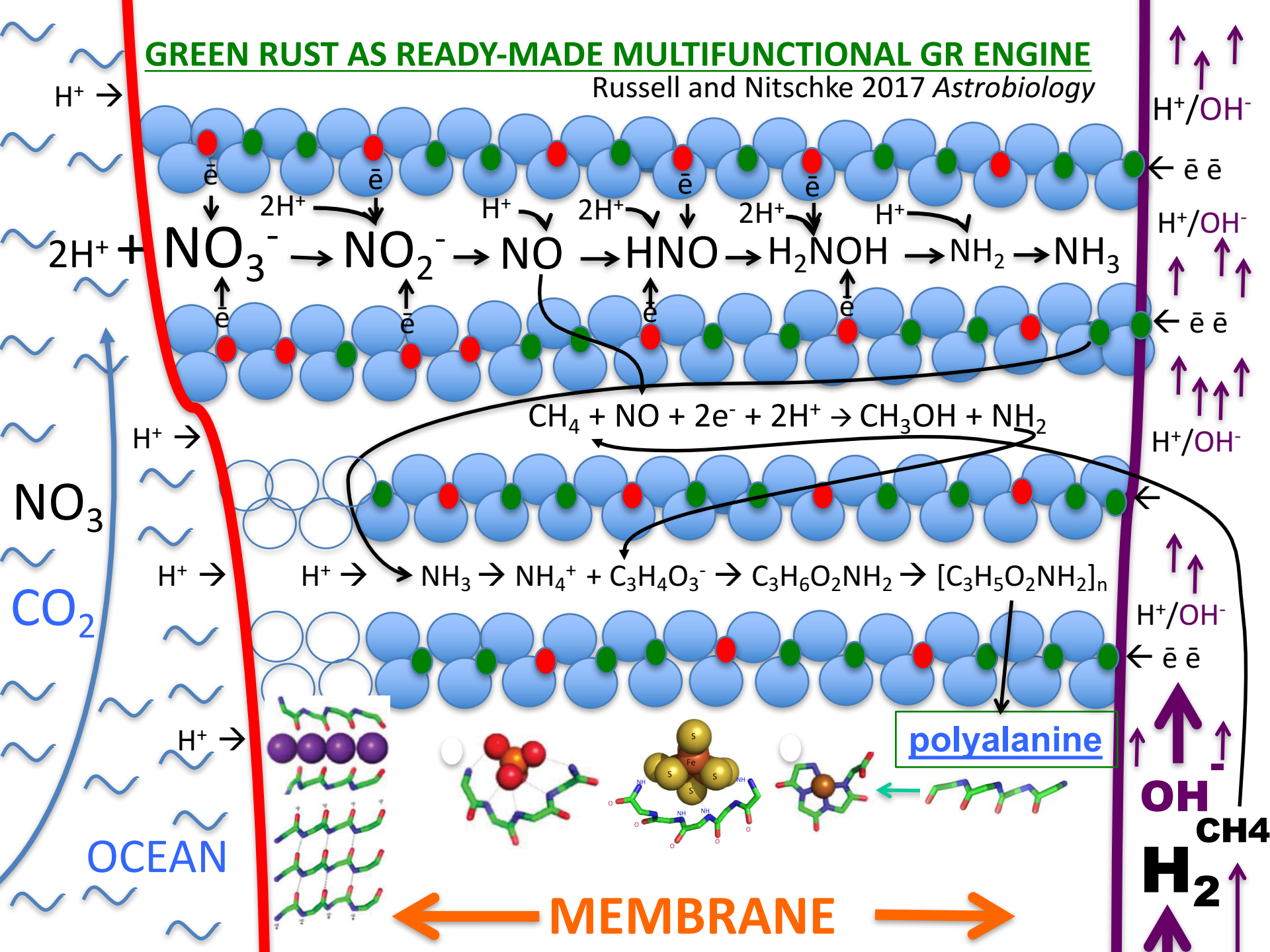


Iron oxy-hydroxycarbonates obtained by <u>protonation</u> and <u>deprotonation</u> of $GR(CO_3^{2-})$ (Génin et al. 2006 *Solid state sciences* 8:1330-1343)

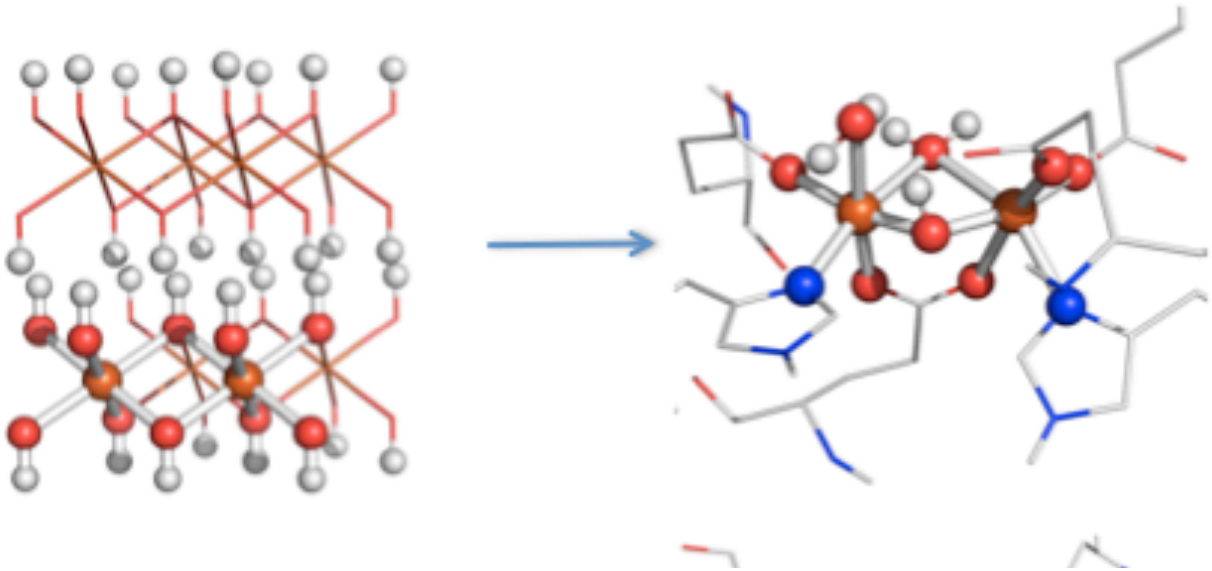

H+ →
OCEAN
NO3 H+ CO2
pH ~5.5, Eh +400mV
green rust nanocrysts
↑ ē ē
H2 CH4 pH ~11 Eh -500mV
H2
ULTRA-MAFIC CRUST
Fe2+4Fe3+2(OH)12CO3.3H2O ⇔ Fe2+2Fe3+4O2(OH)10CO3·3H2O
NO3- → NO2- → NO- → HNO → H2NOH → NH2- → NH3
2H+
H+
2H+
2H+
H+
ē
Diffusion in GR rectified through coupling to redox & pH gradients

GREEN RUST AS READY-MADE MULTIFUNCTIONAL GR ENGINE

Russell and Nitschke 2017 *Astrobiology*



Structure of Green Rust and Methane Monooxygenase active site



iron nitrogen oxygen hydrogen

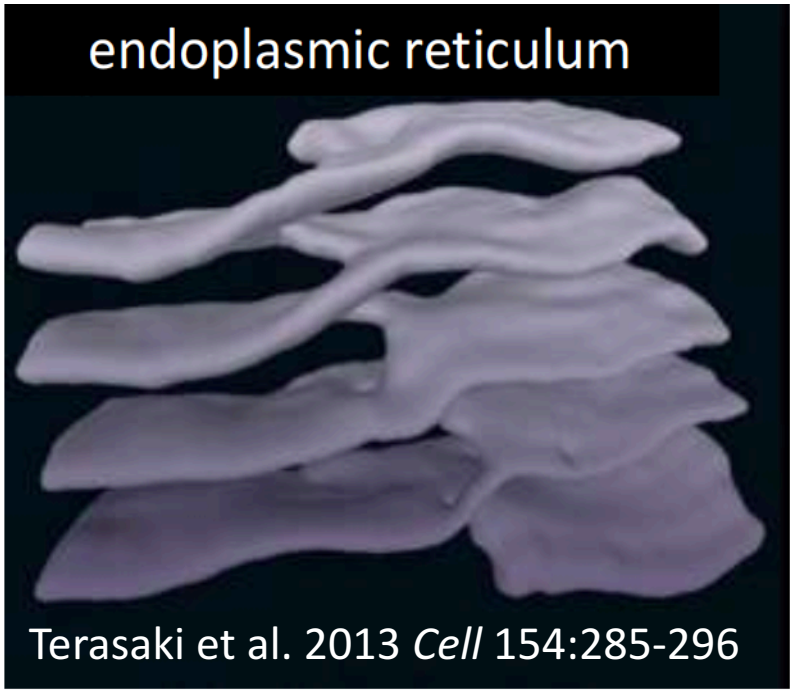
Nitschke et al., 2013 *Biochim Biophys Acta* 1827:871–881

How bodily surface can keep pace with volume – the parking garage structure

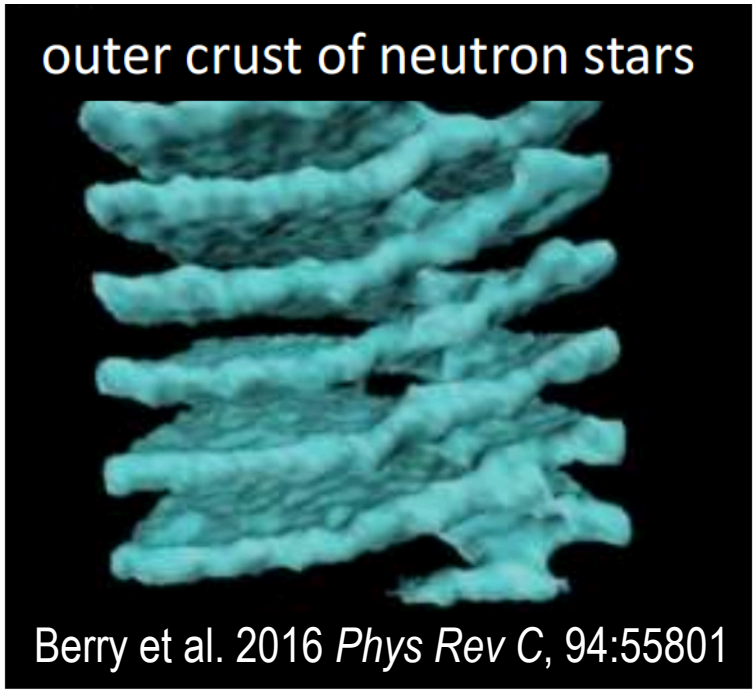
cf. expansion of a sphere

$V = 4\pi r^3/3$

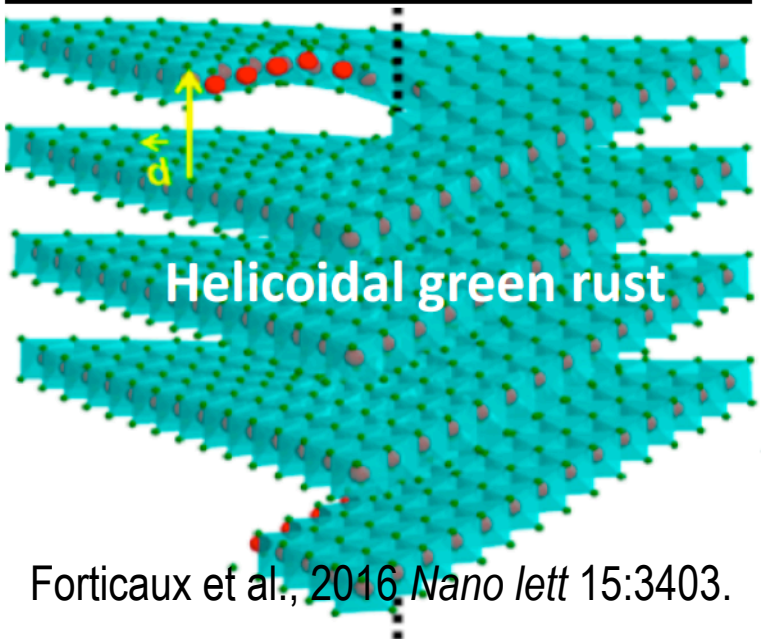
$S = 4\pi r^2$



Terasaki et al. 2013 *Cell* 154:285-296

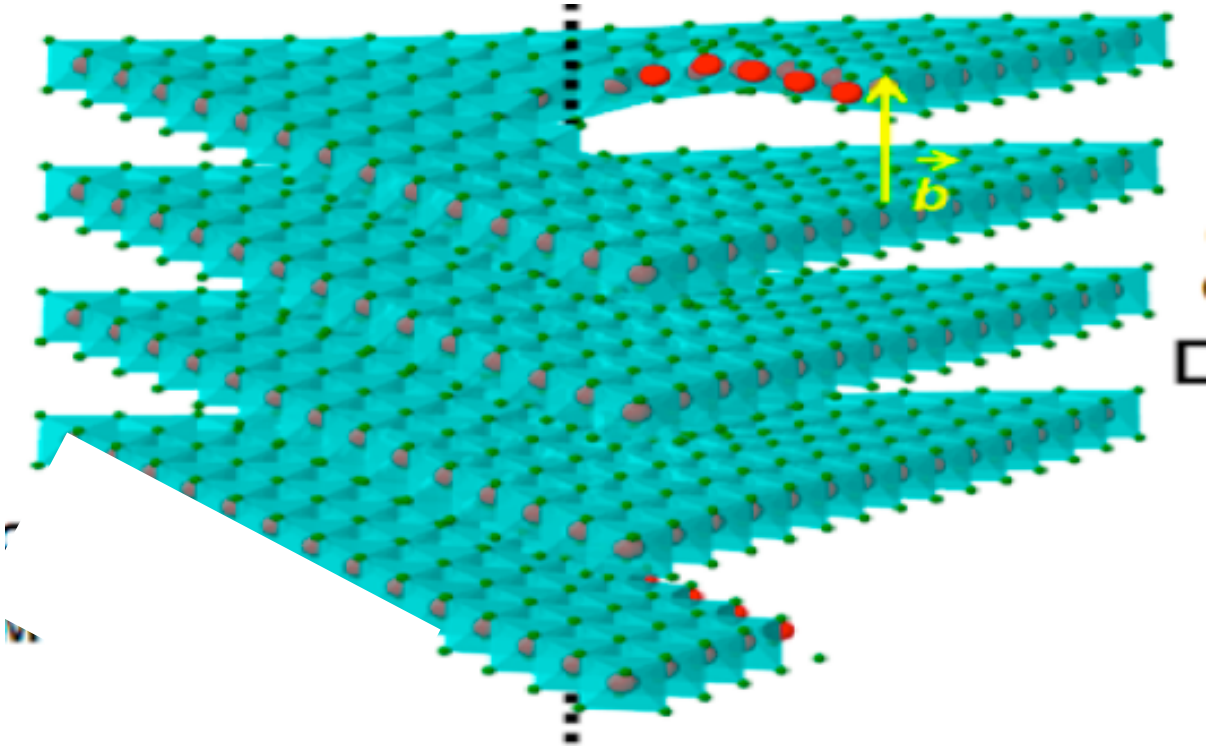


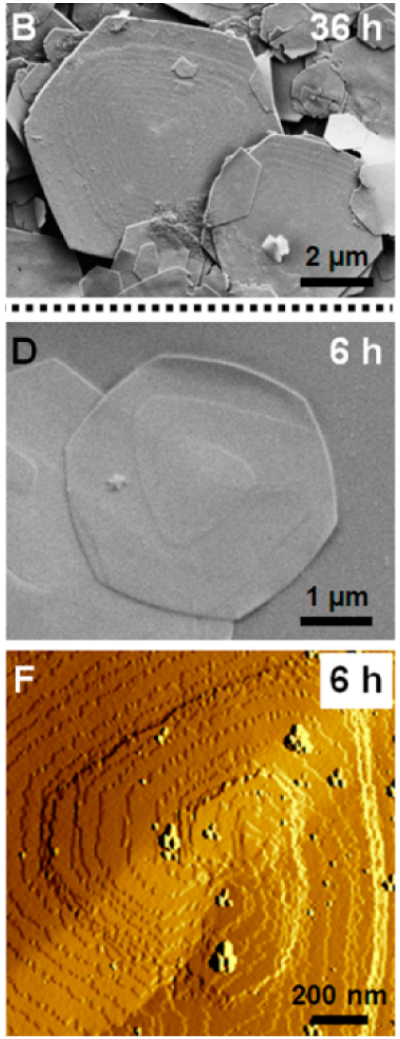
Berry et al. 2016 *Phys Rev C*, 94:55801



Forticaux et al., 2016 *Nano lett* 15:3403.

“Ready made” garage parking structure or helical baffle
In this case function follows form !

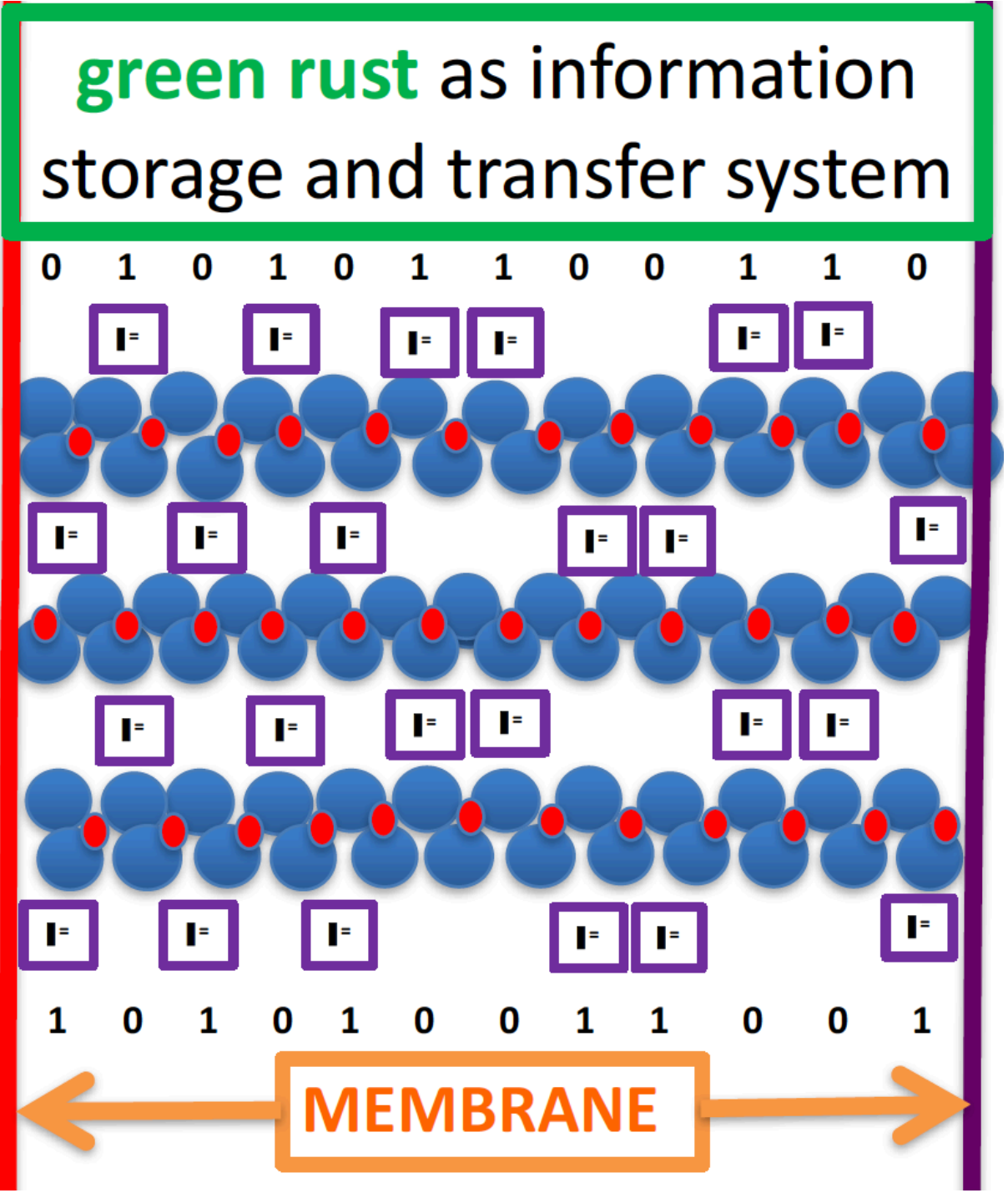




Forticaux, Dang, Liang, Jin (2015) Controlled synthesis of layered double hydroxide nanoplates driven by screw dislocations. *Nano letters*, 15, 3403.

Cf. Double layer hydroxide such as “green rust”

~ $Fe^{II}_4Fe^{III}_2[OH]_{12}CO_3 \cdot 3H_2O$ <-> $Fe^{II}_2Fe^{III}_4O_2(OH)_{10}CO_3.3H_2O$



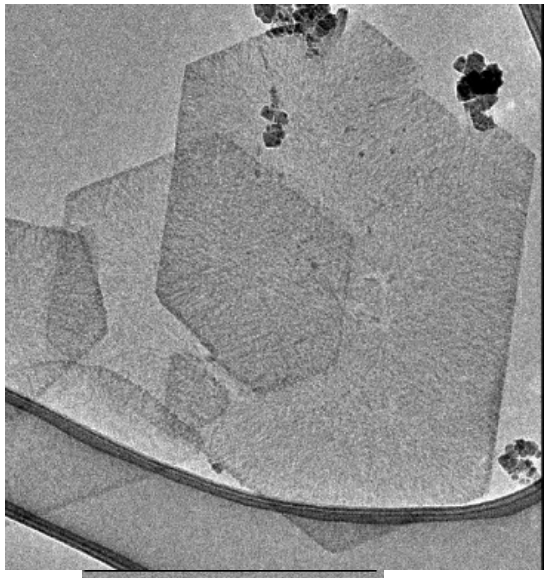
A digital computer?

Fe^{2+} = ZERO

Fe^{3+} = ONE

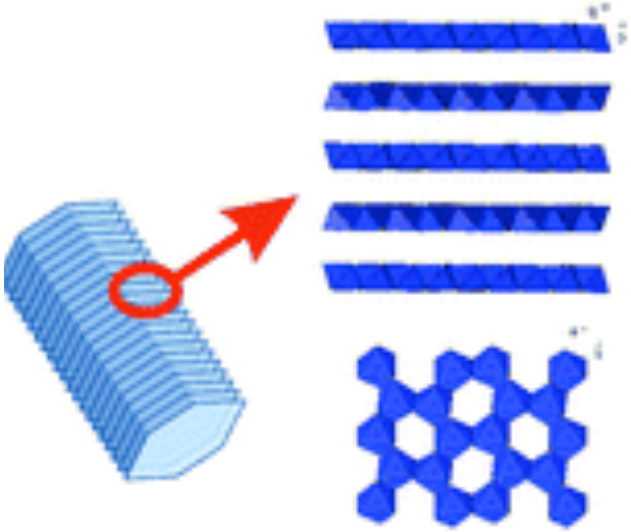
Greenwell & Coveney 2006
After Figure 6
OLEB, **36**, 13-37.

Russell & Beckett 2017
ABSCICON abstract 3192

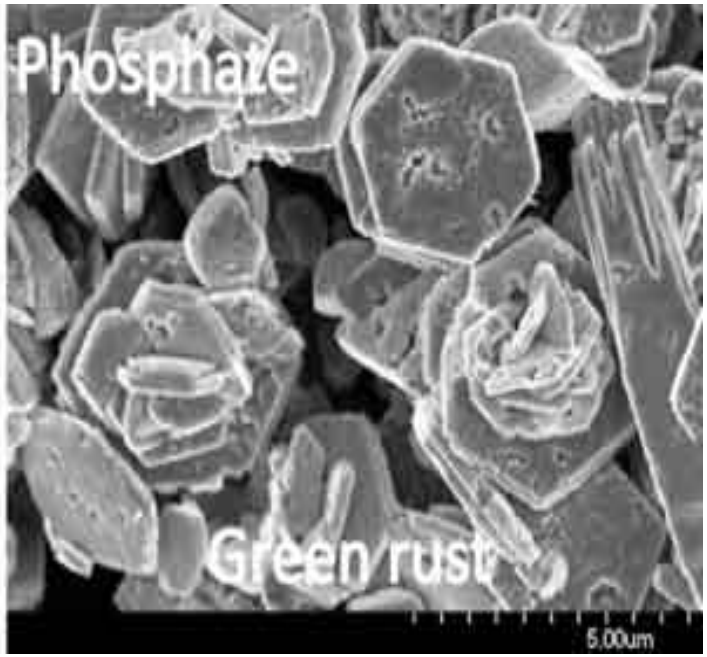


Johnson et al. 2015 Am Min 100:20, Fig 6k

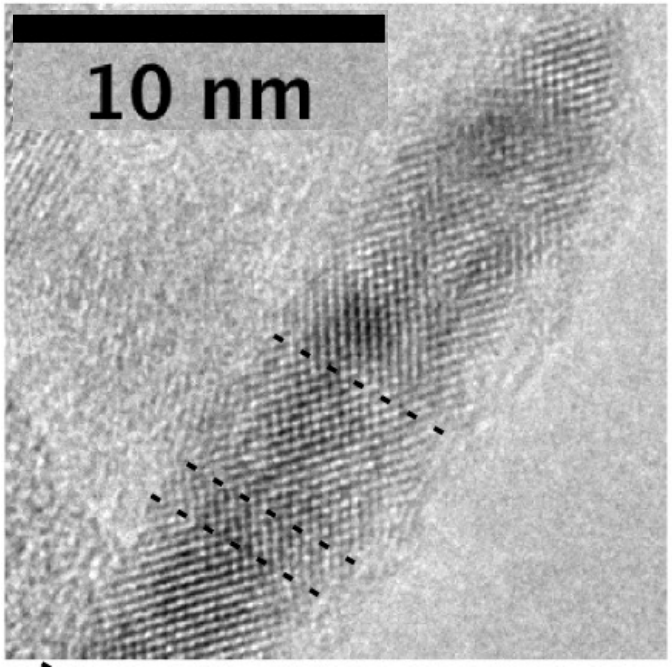
Division (?) of screw dislocated (helicoidal) GREEN RUST



Wang & O'Hare 2012 *J Materials Chem* 22:23064-23070

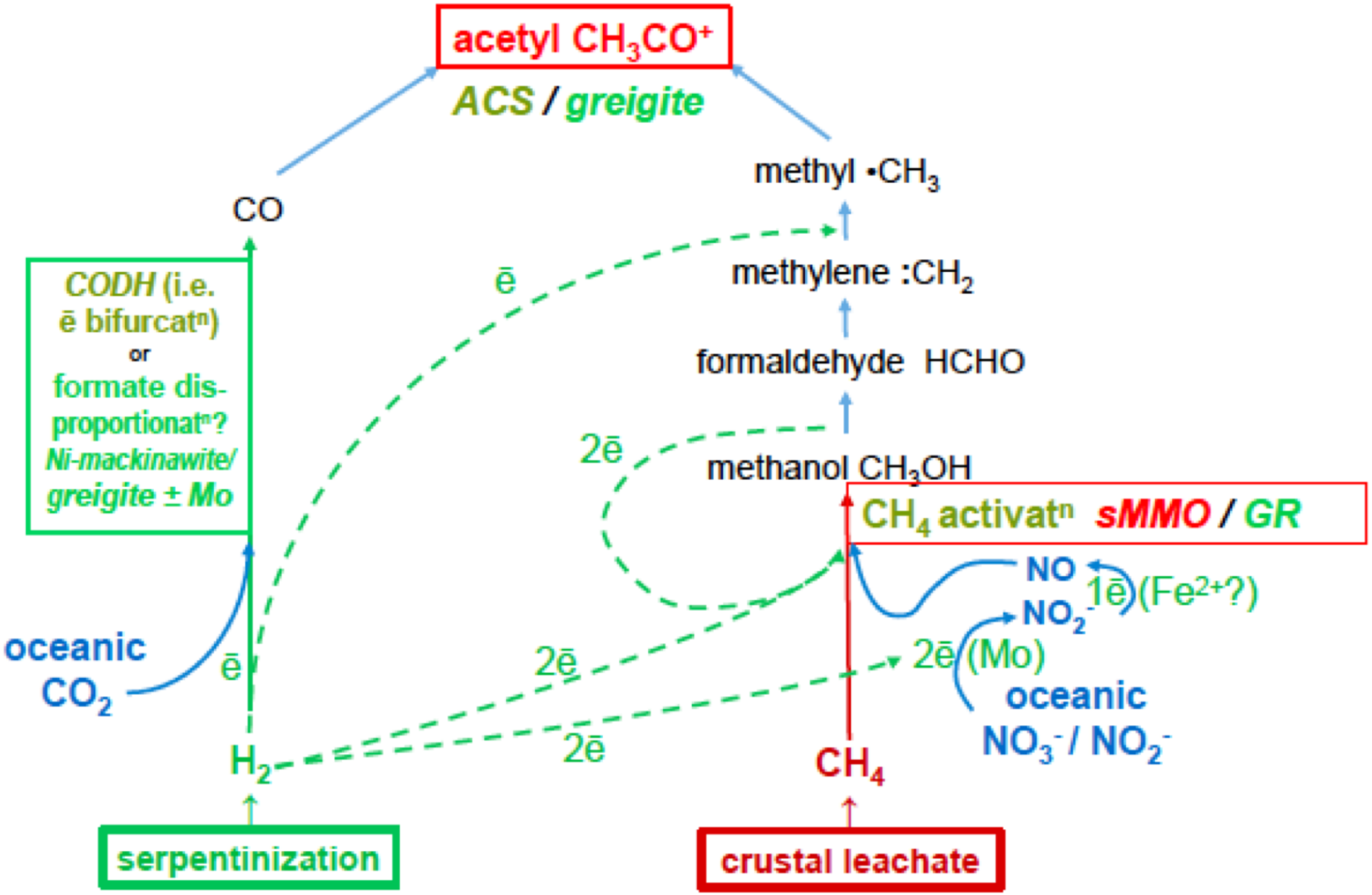


O'Loughlin et al. 2015 *Curr Inorg Chem* 5:214
Hansen & Poulsen 1999 *Clays Clay Miner* 47:312

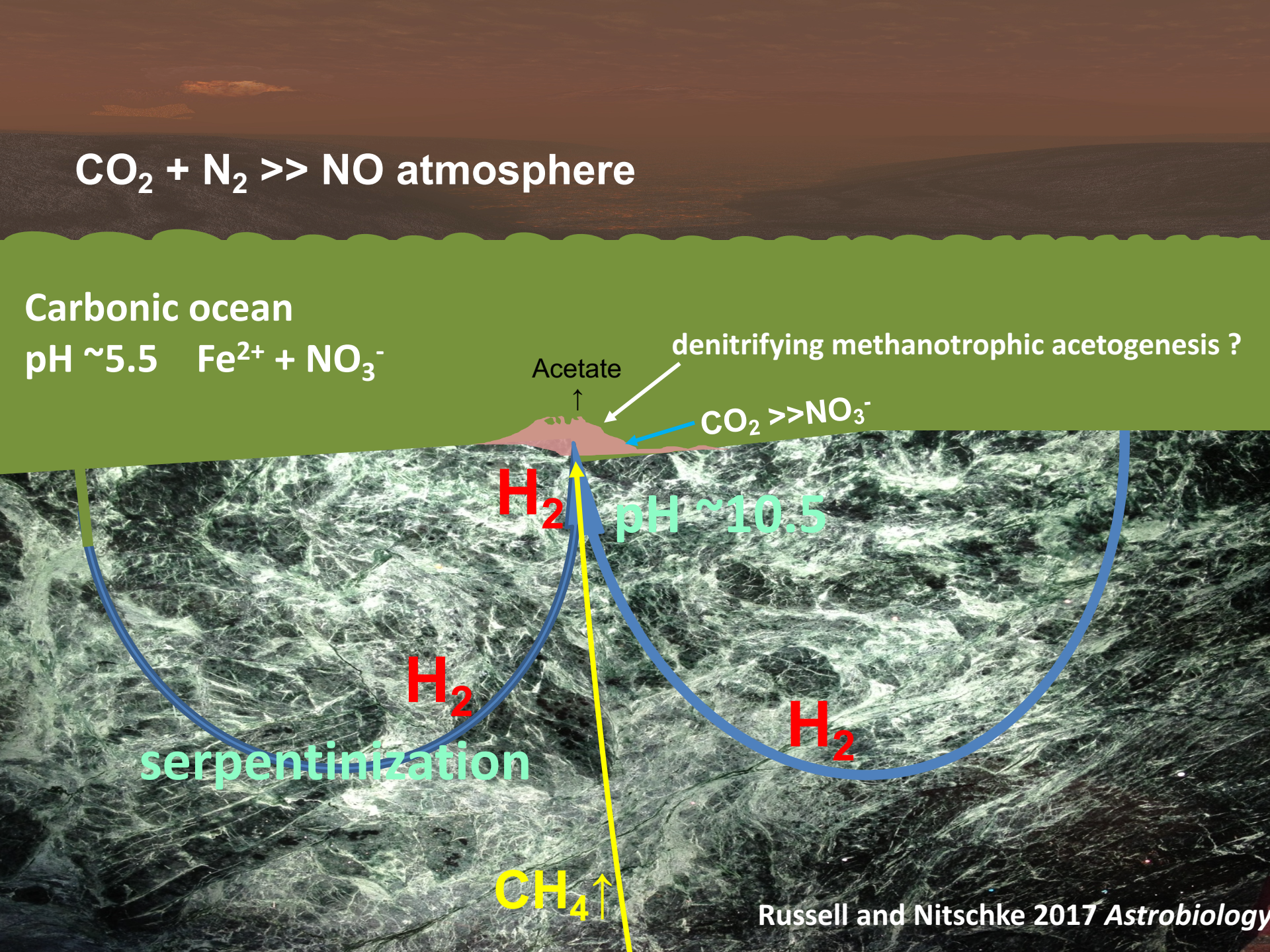


Green rust nanorod; Johnson 2015 Am Mineralogist 100:2091-2105

Denitrifying methanotrophic acetogenesis



Nitschke and Russell 2013 *Phil Trans R Soc Lond B.* 368, 20120; Russell and Nitschke 2017 *Astrobiology*


$CO_2 + N_2$ >> NO atmosphere
Carbonic ocean
pH ~5.5 $Fe^{2+} + NO_3^-$
Acetate
denitrifying methanotrophic acetogenesis ?
CO_2 >>NO_3^-
H_2
pH ~10.5
H_2
H_2
serpentinization
CH_4
Russell and Nitschke 2017 *Astrobiology*

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